NASA TECHNICAL MEMORANDUM

NASA TM X-1066

NASA TM X-1066

GPO PRICE $ ______

OTS PRICE(S) $ 3.00

Hard copy (HC) ______

Microfiche (MF) $1.50

N65-18605

(ACCESSION NUMBER) (THRU)

53 1

(PAGES) (CODE)

31

(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

FACILITY FORM 602

AN EVALUATION OF GEMINI HAND CONTROLLERS AND INSTRUMENTS FOR DOCKING

by Byron M. Jaquet and Donald R. Riley

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

NASA TM X-1066

AN EVALUATION OF GEMINI HAND CONTROLLERS AND INSTRUMENTS FOR DOCKING

By Byron M. Jaquet and Donald R. Riley

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $3.00

AN EVALUATION OF GEMINI HAND CONTROLLERS

AND INSTRUMENTS FOR DOCKING

By Byron M. Jaquet and Donald R. Riley
Langley Research Center

SUMMARY

18605

A simulation study was conducted using the Langley visual docking simulator to evaluate prototype Gemini hand controllers and instruments for docking with six astronauts and four research pilots as subjects. The results of the investigation have indicated that the particular translation controller employed was generally unsatisfactory because of looseness in the mechanism, uneven forces about each axis, and some binding in the mechanism. The attitude controller was rated very satisfactory for docking. All participants felt that the basic design and the location of both controllers were satisfactory. A scaling of 5 degrees per second for about a 1-inch maximum deflection of the angular-rate needles was the preferred value for use with both the rate-command and direct attitude control modes. The range-rate instrument was found to be adequate for the docking maneuver.

AUTHOR

INTRODUCTION

The present investigation was made to evaluate, for the docking phase of Project Gemini, the adequacy of proposed hand controllers and of range and range-rate instruments and to determine a preferred scaling for the angular-rate display. The evaluations were made during simulated docking flights with the Langley visual docking simulator. This simulator is of the fixed-base type and employs closed-circuit television to provide full-scale images of the Agena target vehicle from which maneuvering cues are obtained.

Pilot-controlled simulated docking flights were made with six astronauts and four research pilots as the subjects. A number of familiarization docking flights were made by each subject prior to participation in the evaluation program. Data were obtained by using the primary (rate-command) and backup (direct or acceleration-command) attitude control modes for the docking maneuver from an initial relative range of about 300 feet. The target vehicle was fully lighted for the study. The participants were requested to select a preferred scaling value for the angular-rate display from three different scalings presented. Comments were also requested on the two attitude control modes, the adequacy of the range and range-rate instrument, and the suitability of the translation and attitude controllers for the docking maneuver.

The results of the present investigation are summarized in the form of pilot opinion and pilot ratings concerning the adequacy of the hand controllers, attitude modes, and instruments for docking. In addition, representative trajectories are presented for one astronaut. The displacements, velocities, fuel consumed, and flight time at the terminal condition are presented for all participants. The maximum angular rates used by all participants are also tabulated.

EQUATIONS OF MOTION

Six-degree-of-freedom equations of relative motion between the Agena target vehicle and the Gemini spacecraft were used in the simulation with the axes systems shown in figure 1. The equations of motion are presented in appendix A, and the symbols used herein are defined in appendix B.

DESCRIPTION OF GEMINI, AGENA, AND SIMULATOR

Gemini

The Gemini spacecraft consists of reentry and maneuvering units which are joined together at the heat shield located just behind the astronauts. (See fig. 2.) The maneuvering unit contains all the engines used during the docking phase. These engines include eight translation engines and eight attitude-control engines, all of which use hypergolic fuels. All the engines are located rearward of the center of gravity. As a result, coupling occurs between vertical- and lateral-translation control inputs and the pitch and yaw motions of the spacecraft. The pitch and yaw control inputs similarly produce vertical and lateral translations.

Two basic attitude control modes are available in the spacecraft for docking. The primary mode is rate command in which angular rate about each body axis is proportional to controller deflection. (See section entitled "Simulator" for additional information.) The presence of rate feedback in the rate-command system effectively compensates for the coupling of the translation control inputs into the angular motions. The backup mode is a direct on-off acceleration-command system. With this mode the astronaut must provide, manually, the corrections necessary to account for the coupling effects. Translation maneuvering is performed with an on-off acceleration-command system and the astronaut must manually provide the corrections necessary to account for the coupling of the pitch and yaw control inputs into the translation motions. Two three-axis hand controllers are used to activate the translation and attitude engines. The controllers used in the simulation are described in the simulator section.

Agena

The Agena target vehicle (fig. 2(a)) has a 5-foot-diameter shock-mounted docking ring on the front which serves to channel the Gemini nose to the coupling mechanism. A V-shaped slot in the docking ring and an indexing bar on the Gemini nose provide roll positioning.

Simulator

General arrangement.- An artist's sketch of the Langley visual docking simulator is presented in figure 3. This simulator is of the fixed-base type. The simulator consists of analog-computer equipment combined with a U.S. Air Force aerial gunnery trainer, type F-151, which has been adapted for the study of docking. Included in the gunnery trainer was a closed-circuit television system. A small scale model of the Agena target vehicle was mounted in front of the television camera. The model translates along the camera axis and rotates in three degrees of freedom in response to commands from the pilot through the analog computer. The image of the target is transmitted by the television system to a mirror which is servo driven about two axes. Located directly above the pilot's head, the mirror reflects the image received from the television projection system onto the inside surface of a 20-foot-diameter spherical screen. Through the added action of the mirror system, all six degrees of freedom are simulated. Images of the simulated target vehicle are shown in figure 4. A full-size wooden mock-up of the Gemini spacecraft is mounted within the 20-foot-diameter sphere.

It should be noted that the longitudinal distance between the eyes and the indexing bar was 9.73 feet. (The indexing bar was located on the screen surface and was considered to be at the tip of the Gemini nose for the simulation.) This distance is greater than that for the actual Gemini spacecraft. The use of the longer distance was necessitated in order to avoid complex parallax corrections associated with the simulation display.

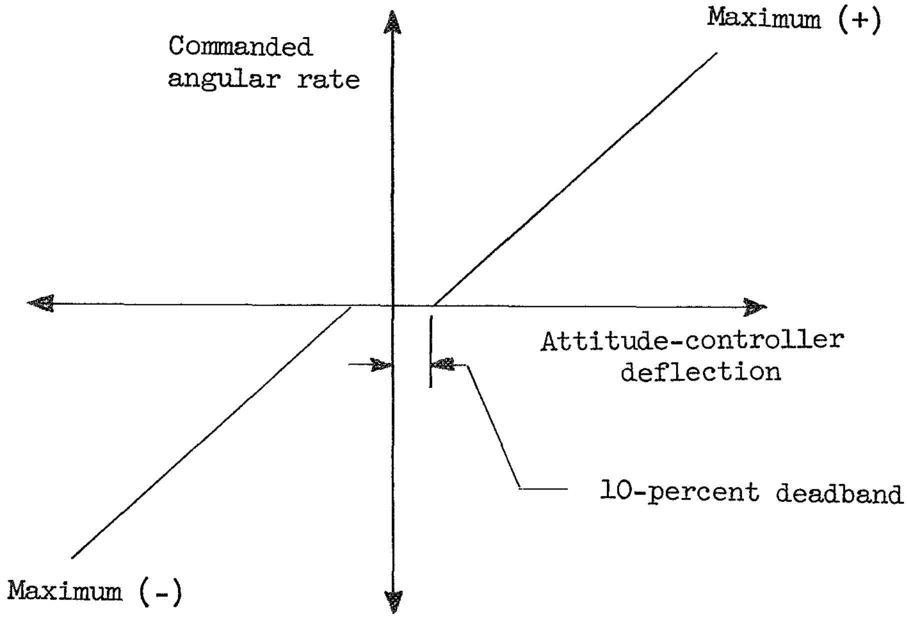
Since the pilots were seated vertically for comfort in a 1g field in the simulator, the instruments and controllers were rotated in order to maintain the proper relationship with respect to a vertical axis through the subject. Since the simulator could only be operated from the left seat, the attitude controller was necessarily tilted to the right, as seen in figure 5(a). With the pilot's spine in a vertical position, his eyes were located in the proper position with respect to the window. The instruments were then positioned at the correct angle of depression and at the proper distance from the pilot's eyes. (In the actual Gemini spacecraft, the astronauts and their respective instrument panels are inclined right and left from the plane of symmetry containing the longitudinal axis. The attitude controller lies in the plane of symmetry and can be used by either astronaut.)

Hand controllers and instruments.- Prototype Gemini hand controllers were used in the simulation and are shown in figure 5(a). The instrument panel is shown in figure 5(b). With the left hand the pilot maneuvers the translation controller fore and aft, left and right, and up and down with corresponding handle motions. The translation controller actually had a 2-inch-diameter spherical knob instead of the smaller one shown in figure 5(a). The attitude controller, operated by the right hand, enabled the pilot to roll, pitch, and yaw the spacecraft. The deflection characteristics of the controllers used in the present simulation are shown in figures 6 and 7. Looseness, indicated by the displacements along the zero-force axes, and some binding, indicated by the discontinuities in the force-displacement curves of the translation controller, can be seen in figure 6. The thrust input lights for the translation controller shown on the lower left-hand side of the panel (fig. 5(b)) were used in the initial briefings on the controls and then were covered for the test program. Angular rates, attitudes, relative range, and range rate for the Gemini were displayed on two prototype Gemini instruments. Yaw, pitch, and roll attitudes (referenced to the local vertical and the orbital plane) of the Gemini were displayed on the eight ball, and angular rates were displayed on the needles, as shown in figure 5(b). It should be noted that with a rigidly stabilized target and the small ranges involved in the simulation the attitude angles also become referenced to the target vehicle. Docking flights were made with the maximum needle deflections of the angular-rate display corresponding to either 5, 10, or 15 degrees per second about each of the axes. Evaluation of the range and range-rate instrument was limited to the suitability of the range-rate scale of ±5 feet per second located on the center of the instrument. The other range-rate scale and the range scale were designed primarily for the rendezvous phase and thus lacked sensitivity for the docking range simulated.

Translation system.- The translation, or maneuvering, system provided maximum thrust when the controller deflection was such that the microswitches (fig. 6) were engaged. (See fig. 5(a) for photograph of translation controller.)

Rate-command attitude mode.- Within the rate-command system the angular rate commanded by a given attitude-controller deflection is compared with the actual vehicle rate to determine an error signal. The error signal is used to activate the pairs of attitude engines. (See fig. 2(b).) The engines operate until the error signal is decreased to within a deadband of 0.2 degree per second. (All three axes have the same deadband.) Maximum controller deflections of about $\pm 10^{\circ}$ about the appropriate axis provide maximum angular rates of ±15 degrees per second in roll and ±10 degrees per second in pitch and yaw. The variation of angular rate with controller deflection used in the simulation is illustrated in sketch (a).

Direct attitude mode.- The direct attitude mode was an on-off system providing maximum thrust when the controller deflection exceeded a 10-percent deadband. A few flights were made with a 50-percent deadband but in insufficient quantity to evaluate in any manner other than with pilots' first impressions.



Sketch (a)

RESULTS AND DISCUSSION

Scope of Investigation

The present investigation was conducted to evaluate, on the basis of pilot opinion, the adequacy of proposed Gemini hand controllers, range-rate instrument, and attitude modes and to determine a preferred scaling for the angular-rate display during the docking phase of Project Gemini. Pilot-controlled simulated docking flights were made using the Gemini prototype display instruments and hand controllers previously described and shown in figure 5. Six astronauts and two research pilots participated in the complete program; two additional research pilots made a number of docking flights but did not participate in the pilot-opinion phase of the program. Visual display of the target (fig. 4) was provided at all times by the closed-circuit television system previously described. Docking tolerances as specified at contact were 1.5 feet per second in longitudinal velocity, ±0.5 foot per second in vertical and lateral velocity, ±1 foot in vertical and lateral displacement of the nose relative to the target, and relative angular misalinements of ±10° about each axis. The velocity tolerances are the most critical since damage to the spacecraft, the target vehicle, or both could occur in the actual mission if contact is made at velocities higher than the tolerances. If displacement or angular tolerances were exceeded at contact in an actual mission, the astronauts could back up and try again, or, if these tolerances were only slightly exceeded, some slight additional maneuvering could be made to bring the contact conditions within the proper tolerances. In the simulation, the pilots were allowed to maneuver, with no time specified to complete docking, only up to the point at which the runs were terminated. The termination point was such that the longitudinal distance for proper contact would place the indexing bar of the spacecraft in the front plane of the docking ring. Therefore, since additional maneuvering is not permitted after a flight is terminated, the simulation results are more pessimistic than those obtained in the actual space mission. The terminal position for perfect docking was demonstrated to each participant. Continuous time-history and terminal data were recorded for each flight. Some of these data are presented and discussed subsequently.

Initial Conditions

Docking flights, for familiarization of the participants with the system operation, were made with initial conditions of $x_o = -250$ feet, $y_o = 100$ feet, and $z_o = 75$ feet with zero relative velocities and angular displacements. For the evaluation phase of the program, data flights were made with initial conditions of $x_o = -250$ feet, $y_o = -100$ feet, $z_o = 75$ feet, and $\psi_o = \theta_o = \phi_o = 15^o$ with zero relative velocities. The fully lighted target vehicle was stabilized with respect to the local vertical and orbital plane with its stabilization system holding attitudes to zero about all three axes.

Pilot Opinion

Hand controllers and attitude modes.- Six astronauts and two research pilots participated in the pilot-opinion phase of the evaluation program. The participants were requested to rate the controllers and attitude modes according to the rating schedule presented in figure 8(a). This schedule was originally developed at the Ames Research Center for the evaluation of airplane stability and control characteristics. The translation controller had not been used previously in simulation studies. The attitude controller, however, was used previously in reentry simulation studies. The ratings given the hand controllers and control modes are presented in figure 8(b). On the average, the translation controller (fig. 5) was rated as unsatisfactory (fig. 8(b)) because of looseness in the mechanism, uneven forces about each axis, and some binding when deflected. The looseness and binding can be seen in the curves presented in figure 6. As a result of these deficiencies, precise inputs were difficult to apply. In fact, one participant said that he was unable to use a smooth application of force and was required to apply forces with a batting motion. Docking could successfully be completed with the controller, however. As a result of this and other investigations, the controller has been redesigned and rebuilt to eliminate the objectionable characteristics.

All the ratings for the attitude controller were in the satisfactory region. (See fig. 8(c).) Adjustments can be made in the attitude controller to provide somewhat different force-deflection curves than those shown in figure 7. All participants felt that the basic design of the controllers and their location were satisfactory. The ratings for the two basic attitude control modes are shown in figure 8(c). The primary rate-command mode was, on the average, well into the satisfactory region, whereas the direct backup mode was, on the average, just barely satisfactory.

Pilot proficiency undoubtedly would affect the pilot-opinion ratings previously discussed. For this program the participants had, on the average, about 25 docking flights which covered various attitude modes and target lighting conditions. (The data for these tests are too meager for inclusion herein.) For some of the astronauts this experience was their first introduction to Gemini characteristics. Some of the astronauts had previously used the attitude controller in reentry simulation studies. Research pilots C and D had participated in docking studies with this simulator using only the out-of-the-window display for guidance information and different dynamics as a result of a different center-of-gravity position. They had not previously used the prototype Gemini controllers.

Instruments for docking.- Prototype Gemini instruments were included in the program for evaluation during docking. These instruments included an angular-rate and attitude instrument and a range and range-rate instrument as shown in figure 5(b). The participants were requested to state a preference for scaling for maximum deflection of the angular rate needles from 5, 10, or 15 degrees per second. A scaling of 5 degrees per second was preferred for both the rate-command and direct attitude modes. As previously mentioned, the range meter did not have the sensitivity required for the range simulated and was not used by the participants. A majority of the participants used the range-rate instrument to aid in establishing an initial closing velocity and thereafter did not use it appreciably. They indicated that the instrument was adequate in this respect for docking. The attitude indicator was found to be useful if it displayed information relative to the target vehicle, but the participants believed that the indicator was not really necessary if the target could be viewed from the spacecraft.

When asked to state a preference for one instrument, one astronaut indicated that no instruments were necessary since he could obtain all maneuvering information from observations of the target through the window. Four astronauts preferred angular-rate information above all other information, and two of the research pilots preferred that only range rate be displayed.

Piloting technique.- Of the two methods attempted to establish an intercept with the target vehicle, the preferred technique for approaching the target was, with one exception, to null the attitudes initially, to translate the spacecraft vertically and laterally to initiate alinement with the target vehicle, and finally to apply a closing velocity. Appropriate initial velocities were used so that the azimuth and elevation angles of the line of sight from the pilot to the target would decrease as range decreased.

The exception was that one astronaut used different techniques depending on the initial relative position of the two vehicles. When approaching the target from the right, he used the same technique as the others. However, a different technique was used when the target was approached from the left. In this case the spacecraft was rotated, and only the longitudinal engines were used to establish an intercept course with the extended longitudinal axis of the target vehicle. This technique supplies the three velocity components of the previous method but requires that pitch and yaw angles be periodically adjusted during the approach so that the target vehicle remains in view. When the intercept point was reached, the attitude angles were near the null position, and vertical- and lateral-translation control inputs were required to stop or reduce the initial transverse velocities. If required, roll corrections were applied at this point in the approach. All the participants used the two techniques several times. Since neither method provides a decisive advantage, the preferred technique was chosen on the basis of personal preference. The latter technique, however, does present an easier piloting task than the former when the direct attitude mode is used because vertical- and lateral-translation control inputs are applied only in the final approach; thus, the coupling effects of these inputs into the angular motions do not exist over the entire trajectory.

Flight Trajectories

Representative trajectories for astronaut E when using the rate-command and direct attitude modes are presented in figure 9. (These trajectories correspond to run 7 of figure 10 and run 8 of figure 11 and the terminal conditions are within the design tolerances.) In these flights, the astronaut first nulled the Gemini attitudes to zero, translated vertically and laterally to initiate initial alinement of the two vehicles, and applied an initial closing velocity. When the direct attitude control mode was used, translation control inputs were generally applied along one axis at a time with several successive short-duration controller motions because of the control coupling effects. With the rate-command mode, sequential single-axis or combined-axis control inputs would be used since the automatic system compensates for the coupling. Some of the participants applied somewhat smaller initial closing rates than those shown in figure 9, but the approach was similar (with the exception noted in the section entitled "Pilot Opinion"). A pilot at peak proficiency with either attitude control mode can make essentially the same type of approach without backing; thus, the backing associated with the direct-mode trajectory (fig. 9) is representative of the state of proficiency reached in the present investigation.

Docking Results

Data obtained at the termination of the docking flights made during the evaluation program are presented in four categories:

	Figure
Astronauts docking with fully lighted target by using:	
Rate-command attitude mode	10
Direct attitude mode	11

Maximum angular rates which were utilized during the docking maneuvers are presented in table I for the astronauts and in table II for the research pilots.

It should be noted that sufficient time was not available for each participant to become proficient in flying both the rate-command and direct attitude control modes. The results are not representative of pilots at peak proficiency and reflect the learning associated with docking under the conditions simulated. Therefore, the lack of a sufficiently large number of flights at each of the specified angular-rate scalings precludes the possibility of determining the effect of angular-rate scaling on the contact conditions for docking. These data are presented only to indicate the range of values encountered and should not be used for statistical analyses because of the small number of individual flights. The data of the present study are presented as a function of consecutive flight number, so that some indication of the relative state of proficiency of each participant can be ascertained. Points are missing for some flights in which the participant lost control or the equipment became overloaded, necessitating the premature termination of a flight before contact conditions were reached.

As noted previously, the present study was concerned with docking, in which information from both a display panel and an out-of-the-window display was used. It has been demonstrated in other simulation studies at the Langley Research Center that docking can be satisfactorily completed from ranges up to about 300 feet when only the out-of-the-window display for maneuvering cues is used. (See refs. 1 to 4.)

It should be noted that the values of $\dot{x}$ (velocity of Gemini center of gravity along target X-axis) exceeding 1.5 feet per second in figure 10 for astronaut B resulted from a misunderstanding of the tolerance, and this misunderstanding probably caused the value of $\dot{y}$ to exceed the tolerance also. The values of $\dot{y}$ and $\dot{z}$ include effects of linear velocity of the Gemini center of gravity and the angular velocity that existed at contact; thus, the values of $\dot{y}$ and $\dot{z}$ presented are those at the Gemini nose.

The Gemini spacecraft piloting task was easier with the rate-command mode than the direct mode, as has been established in this and previous simulation studies. (See ref. 3.) This fact is reflected in the data in which more completed rate-command flights were obtained and also for which the end conditions were more uniform than the direct mode flights. The average attitude angles (fig. 10(c)) and angular rates (fig. 10(d)) at contact when the rate-command mode was used were appreciably smaller than those for the direct mode (figs. 11(c) and 11(d)). Also, the angular rates at contact with the rate-command mode were generally at or near the deadband of 0.2 degree per second. High angular rates at contact may result in the linear velocity tolerances to be exceeded even though the spacecraft has low translational velocities.

Time to complete docking was generally more consistent when the rate-command mode was used. Fuel consumption varied widely with successive flights with either mode of control. (Compare figs. 10(e) and 11(e).) Only astronaut A reached a consistently low level of fuel consumption with both the rate-command and direct attitude modes. A previous investigation indicates that with only an out-of-the-window display and for the same initial conditions as those used herein, a pilot at peak proficiency would take about $3\frac{1}{2}$ minutes and use about 14 pounds of fuel with the rate-command mode and would take about $4\frac{1}{4}$ minutes and use about 10 pounds of fuel with the direct mode.

The results for the research pilots (figs. 12 and 13) are, in general, similar to those for the astronauts. The research pilots that participated in the program had some previous docking experience in simulators and, consequently, they had few out-of-tolerance flights at contact.

Tables I and II present the maximum angular rates used during each flight by the astronauts and the research pilots, respectively. The roll rates p are generally less than ±8 degrees per second, and the pitch and yaw rates q and r, respectively, are generally less than ±6 degrees per second. The maximum rates used by the pilots with either attitude control mode never reached the maximum commanded rate possible with the rate-command mode.

CONCLUDING REMARKS

Six astronauts and four research pilots were participants in a study using the Langley visual docking simulator to evaluate prototype Gemini hand controllers and instruments for docking. In addition, the preferred needle scaling for the angular rate display was determined. The results of the study indicate that the attitude-controller rating was very satisfactory for performing the maneuvers required during docking. The translation-controller rating was generally unsatisfactory, although docking maneuvers could be completed with its use. The deficiencies resulting in this unsatisfactory rating were looseness in the mechanism, uneven forces about each axis, and some binding in the mechanism when deflected. The location of both controllers and their method of operation were felt to be satisfactory. Of the three scalings of 5, 10, or 15 degrees per second for maximum needle deflection of about 1 inch presented during the simulated docking runs on the Gemini angular-rate display, a scaling of 5 degrees per second was the preferred value for use with either the primary or backup attitude control modes. The range-rate instrument was found to be adequate for the docking maneuver.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 5, 1964.

APPENDIX A

EQUATIONS USED IN SIMULATION

Force Equations

The force equations are written with respect to a rotating set of axes located in the orbiting Agena. (See fig. 1.) The rotating axes are oriented such that the Z-axis is always directed along the local vertical and pointing toward the center of the earth. The X-axis is restrained to lie in the orbital plane. The Agena body axes and the reference axes are assumed coincident at all times and maintained so by the target stabilization system. With the use of a first-order approximation to the gravity field and the assumption of a vehicle of constant mass, the equations are as follows:

$$\frac{F_X}{m} = \ddot{x} + 2\omega\dot{z}$$

$$\frac{F_Y}{m} = \ddot{y} + \omega^2 y$$

and

$$\frac{F_Z}{m} = \ddot{z} - 2\omega\dot{x} - 3\omega^2 z$$

Terms including ω^2 were found to be too small to be significant for problem scaling on the computer and thus were neglected.

Moment Equations

The moment equations were written with respect to a body system of axes with the origin located at the center of gravity of the Gemini spacecraft. The center of gravity chosen for this investigation corresponds to that for the half-fuel-load condition for the parachute configuration of the Gemini spacecraft.

$$M_{X,b} = \dot{p}I_{X,b} + qr\left(I_{Z,b} - I_{Y,b}\right) + \left(r^2 - q^2\right)I_{YZ,b} + (pr - \dot{q})I_{XY,b} - (pq + \dot{r})I_{XZ,b}$$

$$M_{Y,b} = \dot{q}I_{Y,b} + pr\left(I_{X,b} - I_{Z,b}\right) + (pq - \dot{r})I_{YZ,b} - (qr + \dot{p})I_{XY,b} + \left(p^2 - r^2\right)I_{XZ,b}$$

and

$$M_{Z,b} = \dot{r}I_{Z,b} + pq\left(I_{Y,b} - I_{X,b}\right) + \left(q^2 - p^2\right)I_{XY,b} - (pr + \dot{q})I_{YZ,b} + (qr - \dot{p})I_{XZ,b}$$

Force Transformation

To solve the three translational equations of motion, the forces F_X, F_Y, and F_Z acting on the Gemini spacecraft in the direction of the rotating axes are required. These forces were obtained by using those generated along the body axes of the Gemini spacecraft by the various thrusters together with an Euler angle matrix. The following matrix was employed:

$$\begin{Bmatrix} F_X \\ F_Y \\ F_Z \end{Bmatrix} = \begin{Bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{Bmatrix} \begin{Bmatrix} F_{X,b} \\ F_{Y,b} \\ F_{Z,b} \end{Bmatrix}$$

where, for the order of rotation ψ, θ, and ϕ,

$$a_1 = \cos\theta \cos\psi$$

$$a_2 = \cos\psi \sin\theta \sin\phi - \sin\psi \cos\phi$$

$$a_3 = \cos\psi \sin\theta \cos\phi + \sin\psi \sin\phi$$

$$b_1 = \sin\psi \cos\theta$$

$$b_2 = \sin\psi \sin\theta \sin\phi + \cos\psi \cos\phi$$

$$b_3 = \sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi$$

$$c_1 = -\sin\theta$$

$$c_2 = \cos\theta \sin\phi$$

and

$$c_3 = \cos\theta \cos\phi$$

APPENDIX A

Euler Rate Equations

The rate of change of the Euler angles measured between the rotating reference axes in the Agena and the Gemini body axes is given by:

$$\dot{\psi} = \frac{r \cos \phi}{\cos \theta} + \frac{q \sin \phi}{\cos \theta} - \omega \tan \theta \sin \psi$$

$$\dot{\theta} = q \cos \phi - r \sin \phi - \omega \cos \psi$$

and

$$\dot{\phi} = p + q \tan \theta \sin \phi + r \tan \theta \cos \phi - \frac{\omega \sin \psi}{\cos \theta}$$

where $\omega = 0.0012$ radian per second and is the angular velocity of the Agena in a circular orbit at an altitude of 150 international nautical miles.

Fuel Consumption

The equations used to determine the amount of fuel (in pounds) used for each axis of the Gemini spacecraft are as follows:

$$\text{Fuel used for fore and aft maneuvering} = \sum_{n=0}^{N_X} \frac{\text{Pounds of force, longitudinal engines}}{I_{sp}} \Delta t_n$$

$$\text{Fuel used for lateral maneuvering} = \sum_{n=0}^{N_Y} \frac{\text{Pounds of force, lateral engine}}{I_{sp}} \Delta t_n$$

$$\text{Fuel used for vertical maneuvering} = \sum_{n=0}^{N_Z} \frac{\text{Pounds of force, vertical engine}}{I_{sp}} \Delta t_n$$

$$\text{Fuel used for rolling} = \sum_{n=0}^{N_X'} \frac{\text{Foot-pounds of torque, roll engines}}{l_{X,b} I_{sp}} \Delta t_n$$

$$\text{Fuel used for pitching} = \sum_{n=0}^{N_Y'} \frac{\text{Foot-pounds of torque, pitch engines}}{l_{Y,b} I_{sp}} \Delta t_n$$

$$\text{Fuel used for yawing} = \sum_{n=0}^{N_Z'} \frac{\text{Foot-pounds of torque, yaw engines}}{l_{Z,b} I_{sp}} \Delta t_n$$

where $n = N_X$, N_Y, and N_Z indicates the number of translation control inputs, $n = N_X'$, N_Y', and N_Z' indicates the number of attitude control inputs, and Δt_n is the time for a given control input.

APPENDIX B

SYMBOLS

The symbols used herein are defined as follows:

F_X,F_Y,F_Z total forces along X-, Y-, and Z-axes, respectively, located at midlength of Agena target vehicle, pounds

$F_{X,b},F_{Y,b},F_{Z,b}$ total force along Gemini body axes produced by translation and attitude control inputs, pounds

g acceleration due to earth gravity, ft/sec^2

I_{sp} specific impulse, $\frac{\text{pound-second}}{\text{pound}}$

$I_{X,b},I_{Y,b},I_{Z,b}$ moments of inertia about Gemini body axes, slug-foot^2

$I_{XZ,b},I_{YZ,b},I_{XY,b}$ products of inertia about Gemini body axes, slug-foot^2

$l_{X,b},l_{Y,b},l_{Z,b}$ distances from Gemini center of gravity to thrust vector of attitude engines used to produce moments about body axes, feet

$M_{X,b},M_{Y,b},M_{Z,b}$ moment produced about Gemini body axes by translation and attitude control inputs, foot-pounds

m Gemini mass, slugs

p,q,r angular rates about Gemini body axes, radians/second or degrees/second

Δt_n time for a given control input, seconds

X,Y,Z right-hand body axes system located at midlength of Agena (fig. 1)

X_b,Y_b,Z_b right-hand body axes system located at Gemini center of gravity (fig. 1)

x,y,z distances along X-, Y-, and Z-axes, respectively, feet

ψ,θ,ϕ Euler angles in specified order relating position of Gemini body axes and Agena body axes, degrees or radians (fig. 1)

ω rate of rotation of Agena axes system about earth at an altitude of 150 international nautical miles, 0.0012 radians/second (1 international nautical mile = 6076.115486 international feet)

Subscripts:

nose relative conditions of spacecraft nose at contact

o initial conditions

A dot over a symbol denotes the first derivative with respect to time, and two dots over a symbol denote the second derivative with respect to time.

REFERENCES

1. Jaquet, Byron M.; and Riley, Donald R.: Fixed-Base Gemini-Agena Docking Simulation. A Compilation of Recent Research Related to the Apollo Mission, NASA TM X-890, 1963, pp. 67-78.

2. Jaquet, Byron M.: Simulator Studies of Space and Lunar Landing Techniques. Lectures in Aerospace Medicine. USAF School of Aerospace Medicine (Brooks AFB, Texas), Feb. 3-7, 1964, pp. 145-166.

3. Hatch, Howard G., Jr.; Riley, Donald R.; and Cobb, Jere B.: Full-Scale Gemini-Agena Docking Using Fixed- and Moving-Base Simulators. Paper No. 64-334, Am. Inst. Aeron. Astronaut., June 1964.

4. Pennington, Jack E.; Hatch, Howard G., Jr.; Long, Edward R.; and Cobb, Jere B.: Visual Aspects of a Full-Size Pilot-Controlled Simulation of the Gemini-Agena Docking. NASA TN D-2632, 1965.

TABLE I.- MAXIMUM ANGULAR RATES USED BY ASTRONAUTS DURING DOCKING WITH FULLY LIGHTED TARGET

Astronaut	Attitude control mode	Flight	Maximum angular rates, deg/sec		
			p	q	r
A	Rate command	1	1.93 -4.73	1.78 -1.38	1.72 -.60
		2	2.29 -3.15	2.46 -.26	2.46 -1.58
		3	1.50 -2.44	2.95 -.23	2.52 -3.09
		4	4.44 -4.44	1.66 -.23	2.69 -1.72
		5	2.94 -2.94	5.04 -.23	3.32 -3.27
		6	0.36 -4.87	2.38 -1.72	1.83 -2.46
		7	0.21 -7.23	4.76 -3.38	3.84 -3.72
	Direct	1	3.51 -5.16	2.23 -1.78	2.03 -1.78
		2	9.81 -1.43	1.32 -.89	0.80 -2.55
		3	1.79 -.72	1.32 -1.43	1.89 -1.60
		4	1.36 -1.58	1.78 -1.55	1.95 -2.18
		5	1.94 -3.37	2.75 -1.78	2.44 -1.55
B	Rate command	1	4.15 -2.44	3.84 -1.55	1.92 -3.72
		2	6.30 -8.67	3.24 -3.12	5.73 -5.39
		3	2.58 -3.15	3.35 -.97	3.27 -2.46
		4	1.65 -1.86	3.35 -.23	4.18 -1.55
		5	8.88 -6.30	4.01 -4.10	5.16 -5.73
		6	3.58 -6.23	3.55 -2.92	2.78 -2.70
		7	1.58 -4.58	2.87 -3.75	3.81 -5.04
		8	2.58 -9.31	3.72 -5.73	2.75 -4.30
	Direct	1	4.44 -2.87	3.41 -3.32	2.52 -3.15
		2	7.38 -5.73	5.73 -5.73	3.29 -5.04
		3	1.22 -1.72	3.72 -3.72	2.55 -3.50
		4	7.66 -5.01	5.73 -5.73	4.21 -4.56
		5	4.87 -8.02	3.29 -5.73	2.69 -4.76
		6	4.23 -2.08	3.93 -1.86	2.81 -1.86
		7	7.02 -2.01	3.38 -3.52	4.18 -1.92
		8	7.81 -9.60	3.95 -5.73	5.36 -5.73
		9	4.66 -3.08	5.67 -5.73	2.81 -4.41
		10	2.43 -3.58	3.27 -3.38	2.64 -2.69
C	Rate command	1	5.87 -7.66	3.72 -.23	1.89 -1.20
		2	2.53 -2.79	2.75 -1.15	1.83 -1.60
		3	13.54 -13.18	5.27 -4.84	3.93 -2.01
		4	7.52 -7.59	2.84 -2.49	3.61 -5.73
		5	8.95 -12.32	3.27 -2.55	5.73 -5.44
		6	3.87 -6.09	3.18 -3.55	1.75 -2.87
		7	1.36 -7.09	3.18 -3.55	1.74 -2.87
		8	9.60 -7.74	2.87 -5.73	4.44 -5.73
		9	5.73 -6.02	3.61 -5.73	3.47 -3.90
	Direct	1	12.03 -12.25	5.73 -5.73	5.73 -5.73
		2	12.89 -14.33	5.73 -5.73	5.73 -4.99
		3	3.65 -3.37	5.16 -5.73	5.16 -3.55
		4	13.54 -2.08	3.47 -4.01	2.09 -2.18
		5	9.38 -6.73	5.73 -5.73	2.58 -5.73
		6	2.08 -2.29	3.70 -3.55	2.66 -2.23
D	Rate command	1	3.73 -2.72	4.64 -1.26	3.15 -2.01
		2	4.58 -4.23	4.50 -2.18	3.93 -3.07
		3	4.60 -4.80	3.12 -1.40	3.24 -2.64
		4	3.15 -4.30	4.35 -3.04	5.73 -5.73
		5	3.01 -8.17	2.35 -4.50	3.38 -3.58
		6	1.58 -6.37	4.47 -3.58	5.67 -5.73
		7	6.30 -11.03	3.90 -2.95	5.33 -5.19
	Direct	1	3.72 -4.08	3.61 -1.52	2.72 -4.41
		2	3.44 -5.16	2.03 -2.23	2.35 -3.93
		3	6.30 -3.15	5.27 -2.78	2.35 -5.73
		4	3.94 -2.29	2.29 -1.40	2.18 -2.21
		5	2.58 -3.37	1.95 -2.06	2.92 -3.47
		6	2.87 -2.15	4.01 -1.20	2.69 -2.38
		7	1.15 -3.15	2.12 -2.03	2.09 -1.75
		8	3.80 -2.72	3.50 -2.23	2.38 -4.53

TABLE I.- MAXIMUM ANGULAR RATES USED BY ASTRONAUTS DURING DOCKING WITH FULLY LIGHTED TARGET - Concluded

Astronaut	Attitude control mode	Flight	Maximum angular rates, deg/sec		
			p	q	r
E	Rate command	1	1.22 -2.51	2.63 -1.26	1.12 -1.54
		2	1.93 -1.86	3.09 -.57	0.80 -1.15
		3	1.86 -2.58	1.95 -.23	1.67 -.97
		4	6.30 -8.17	2.89 -2.84	2.29 -5.73
		5	5.16 -6.73	2.12 -4.64	1.83 -4.30
		6	1.29 -5.01	1.46 -3.27	1.55 -3.61
		7	No rate data taken		
	Direct	1	2.01 -2.08	3.32 -1.98	1.83 -1.40
		2	12.68 -9.24	4.99 -3.78	5.73 -5.73
		3	3.72 -6.30	4.96 -2.52	2.29 -2.52
		4	3.58 -5.16	5.73 -2.15	1.58 -1.83
		5	6.95 -6.23	3.50 -3.84	2.41 -2.92
		6	6.73 -6.01	4.27 -2.23	2.12 -1.09
		7	3.01 -2.58	2.87 -3.01	2.35 -3.27
		8	No rate data taken		
F	Rate command	1	0.14 -.21	1.03 -.80	0 -2.01
		2	2.69 -4.01	1.89 -3.67	2.87 -.63
		3	2.58 -5.44	1.52 -1.49	1.66 -.40

Astronaut	Attitude control mode	Flight	Maximum angular rates, deg/sec		
			p	q	r
F	Rate command	4	2.58 -3.72	2.87 -1.72	0.86 -.40
		5	3.58 -4.80	2.58 -2.29	3.78 -.89
		6	3.58 -5.80	2.49 -2.15	1.26 -2.95
		7	2.58 -3.87	3.23 -2.23	2.01 -1.95
		8	3.80 -3.22	1.95 -2.75	2.38 -2.38
	Direct	1	4.51 -3.72	5.56 -2.01	3.09 -5.73
		2	7.88 -4.73	3.13 -1.58	3.21 -2.81
		3	5.66 -3.87	3.32 -3.84	2.72 -3.27
		4	10.03 -3.65	2.46 -1.43	2.81 -3.58
		5	5.87 -8.60	3.72 -2.06	5.21 -5.79
		6	10.60 -8.38	4.99 -5.73	5.27 -3.09
		7	6.45 -8.17	5.04 -1.03	3.90 -2.69
		8	7.52 -8.38	3.61 -2.29	4.10 -5.79
		9	6.37 -8.67	3.44 -4.53	3.98 -3.87
		10	5.52 -6.09	3.35 -2.12	3.78 -3.50
		11	7.59 -10.10	5.67 -5.73	4.76 -4.67
		12	5.23 -6.80	5.84 -3.21	4.07 -3.67

TABLE II.- MAXIMUM ANGULAR RATES USED BY RESEARCH PILOTS WHEN DOCKING WITH FULLY LIGHTED TARGET

Astronaut	Altitude control mode	Flight	Maximum angular rate, deg/sec		
			p	q	r
A	Rate command	1	1.54 -1.58	1.48 -.40	0.69 -.63
		2	0.93 -1.36	1.26 -.15	0.60 -.60
		3	2.29 -2.22	0.63 -.63	0.73 -1.21
		4	1.39 -3.51	1.03 -.15	1.17 -.72
		5	2.51 -2.87	1.27 -.54	1.15 -.85
	Direct	1	3.01 -1.43	1.55 -.92	1.27 -2.41
		2	2.01 -3.22	1.39 -1.75	2.29 -2.06
		3	7.02 -6.12	2.35 -1.95	2.69 -2.06
		4	8.74 -7.52	2.69 -1.44	2.01 -2.18
		5	No rate data taken		
		6	5.16 -4.29	5.39 -2.87	4.76 -2.55
		7	1.93 -1.93	1.95 -1.49	1.72 -1.15
		8	6.51 -7.02	5.16 -4.15	5.27 -4.52
		9	3.80 -3.51	3.58 -1.83	1.66 -2.06
		10	2.15 -3.15	2.23 -3.21	1.89 -2.18
		11	3.65 -2.22	1.72 -1.40	2.32 -1.66
		12	2.87 -2.29	3.04 -2.06	1.72 -4.27
B	Rate command	1	1.83 -3.87	1.32 -.26	3.67 -2.55
		2	0.20 -4.05	3.84 -3.84	1.72 -2.55
		3	0.21 -.29	4.44 -8.88	1.38 -.40
		4	2.29 -6.23	3.09 -3.27	1.55 -1.80
		5	1.72 -.25	2.95 -3.28	3.67 -5.73
	Direct	1	2.01 -7.19	2.15 -2.18	2.12 -1.66
B	Direct	2	0.39 -1.93	1.89 -2.35	1.69 -1.80
		3	1.22 -1.58	1.58 -2.12	1.26 -1.49
		4	2.44 -2.72	2.46 -2.32	1.66 -2.64
C	Rate command	1	2.51 -10.74	3.72 -2.81	1.83 -2.35
		2	4.44 -11.46	1.38 -.92	1.81 -4.87
	Direct	1	3.15 -4.23	2.69 -3.21	2.92 -2.75
		2	2.65 -3.58	3.38 -5.73	3.07 -3.24
		3	4.73 -3.08	1.55 -3.12	5.33 -2.87
		4	3.37 -4.15	2.64 -3.32	1.63 -2.29
		5	1.72 -2.36	1.72 -3.87	1.95 -2.55
D	Rate command	1	0.21 -2.58	2.84 -.23	1.35 -.26
		2	0.21 -3.08	4.53 -1.30	2.41 -.26
		3	3.65 -2.79	4.58 -3.44	2.46 -.97
		4	0.17 -6.73	5.84 -1.66	3.95 -5.67
		5	3.44 -3.01	5.44 -.23	1.73 -.26
		6	0.20 -6.69	2.25 -1.15	1.32 -2.64
		7	2.58 -8.74	2.58 -.23	0.86 -2.29
		8	0.20 -6.62	0.23 -.23	0.23 -3.27
	Direct	1	2.87 -.29	1.49 -3.15	2.16 -1.72
		2	4.66 -6.44	1.80 -3.95	3.47 -5.38
		3	3.72 -5.66	3.35 -3.11	2.02 -1.27
		4	7.79 -7.45	5.57 -5.22	4.74 -3.51

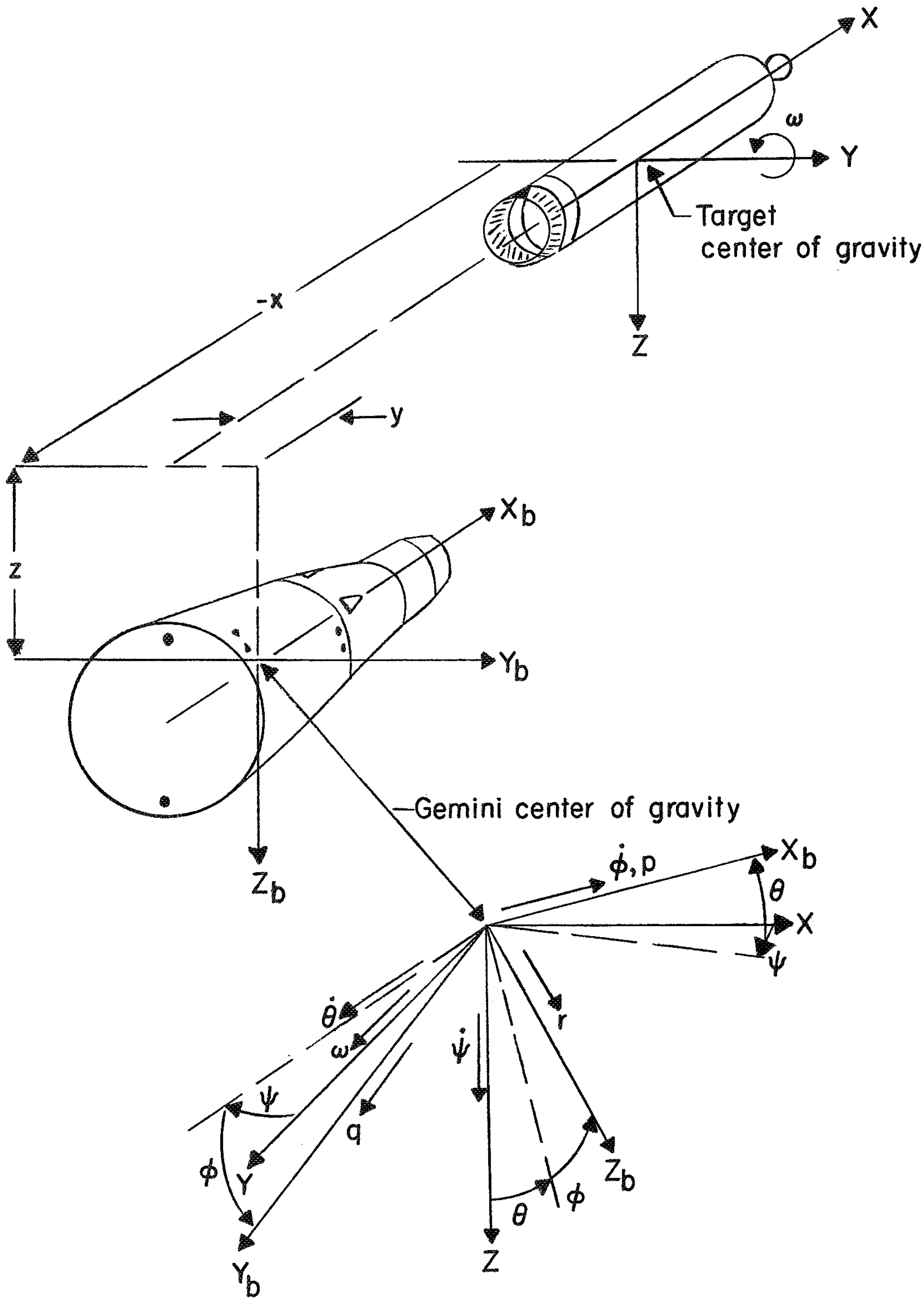
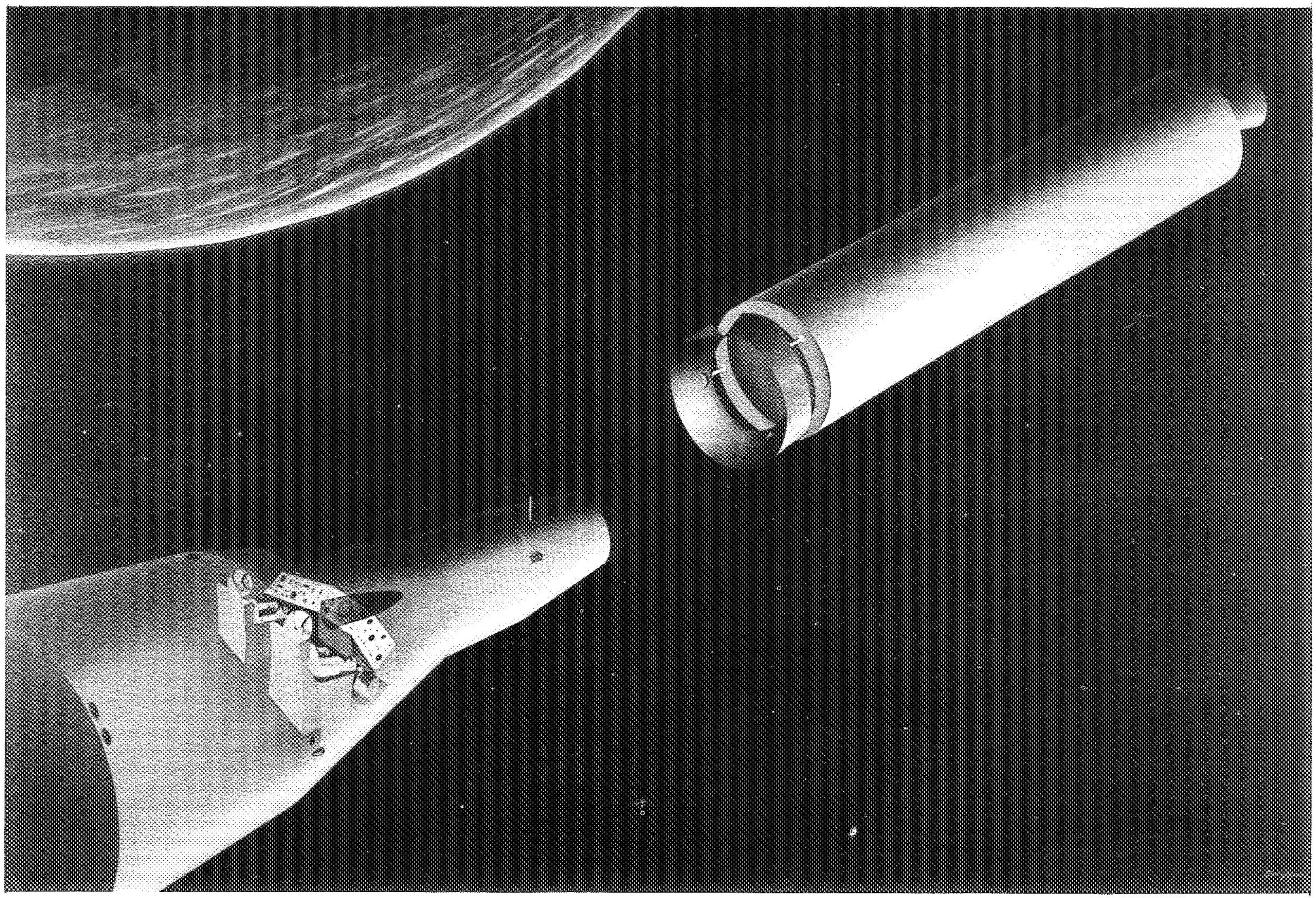
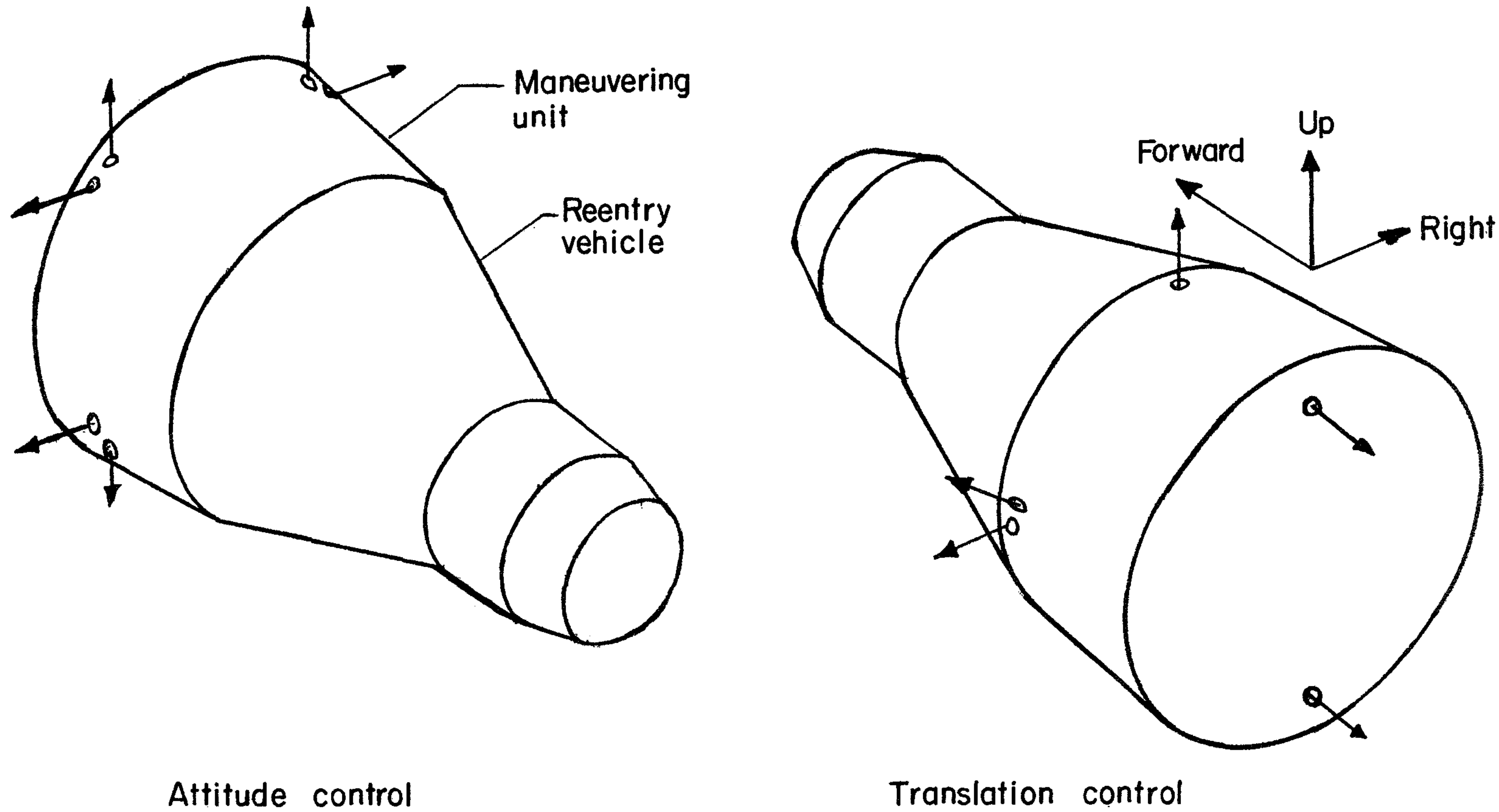


Figure 1.- Systems of axes.



(a) Artist's illustration of Gemini and Agena near contact. L-62-3375

Figure 2.- Gemini spacecraft and Agena target vehicle.



(b) Illustration of Gemini orbital attitude and maneuvering system.

Figure 2.- Concluded.

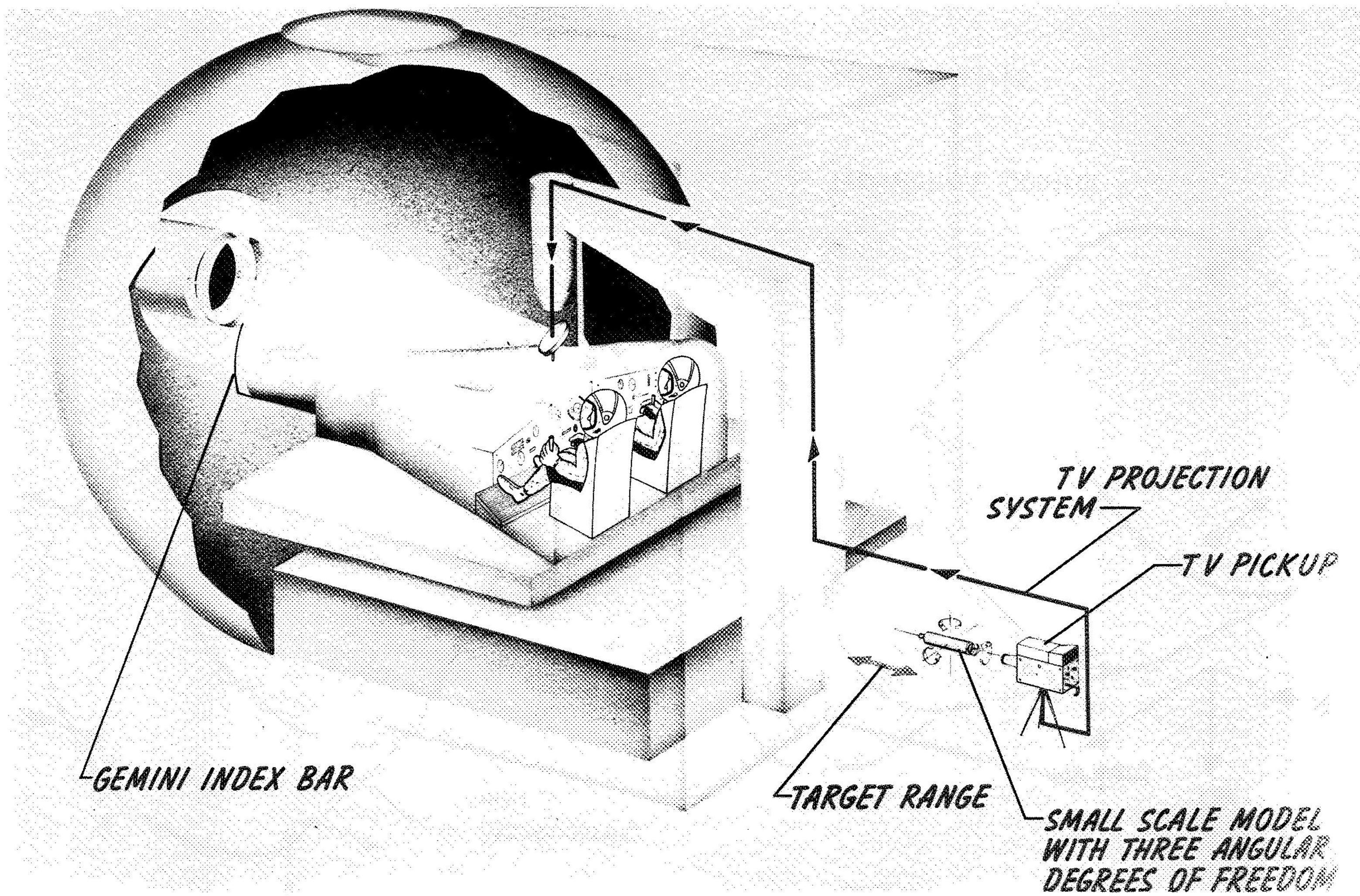
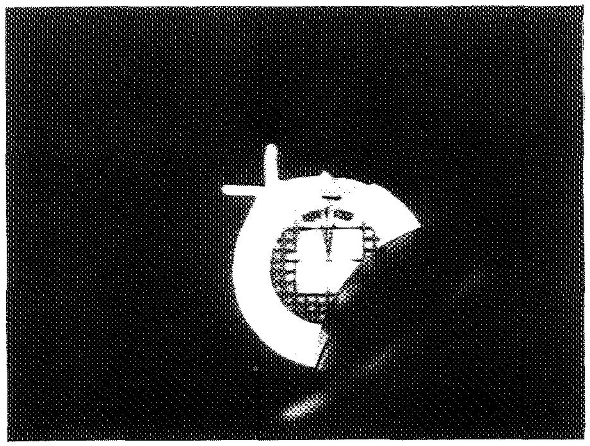
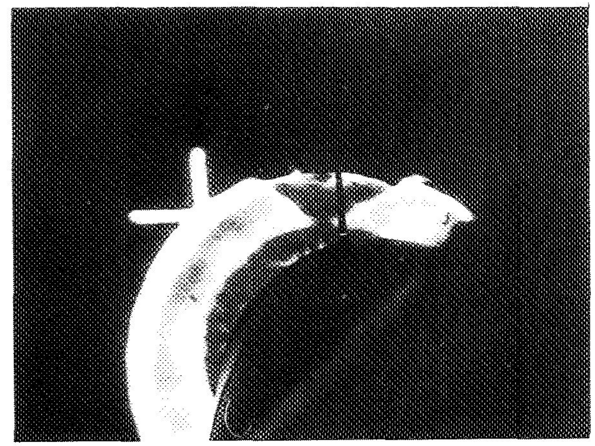


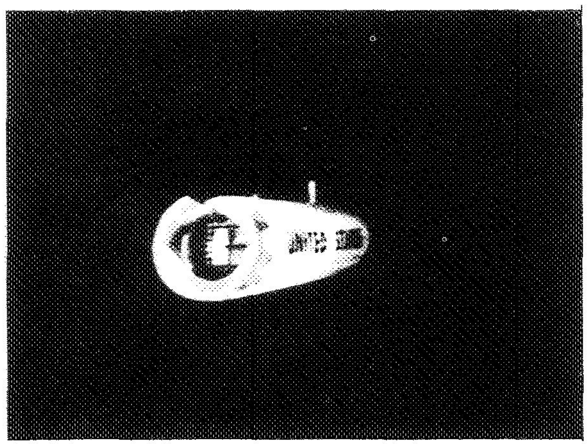
Figure 3.- Artist's illustration of Langley visual docking simulator. L-2202-4



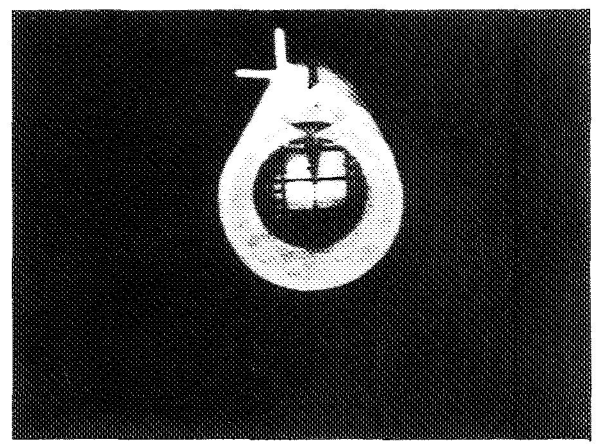
(a) Short longitudinal distance from contact with Gemini and Agena center lines alined; no angular misalinements.



(b) Ideal terminal conditions for docking flight with Gemini and Agena center lines alined; no angular misalinements.



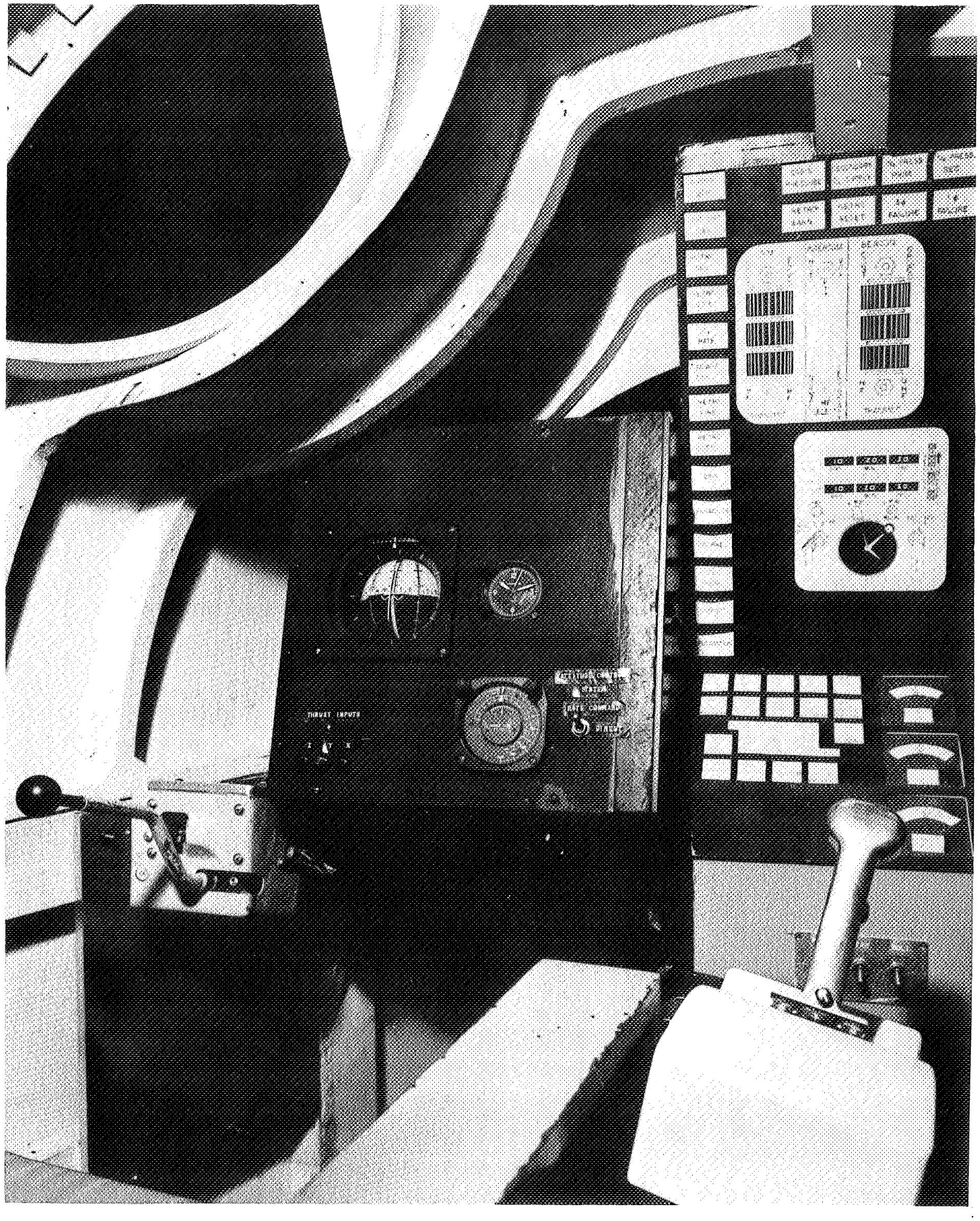
(c) Gemini displaced laterally.



(d) Gemini displaced vertically.

L-64-8399

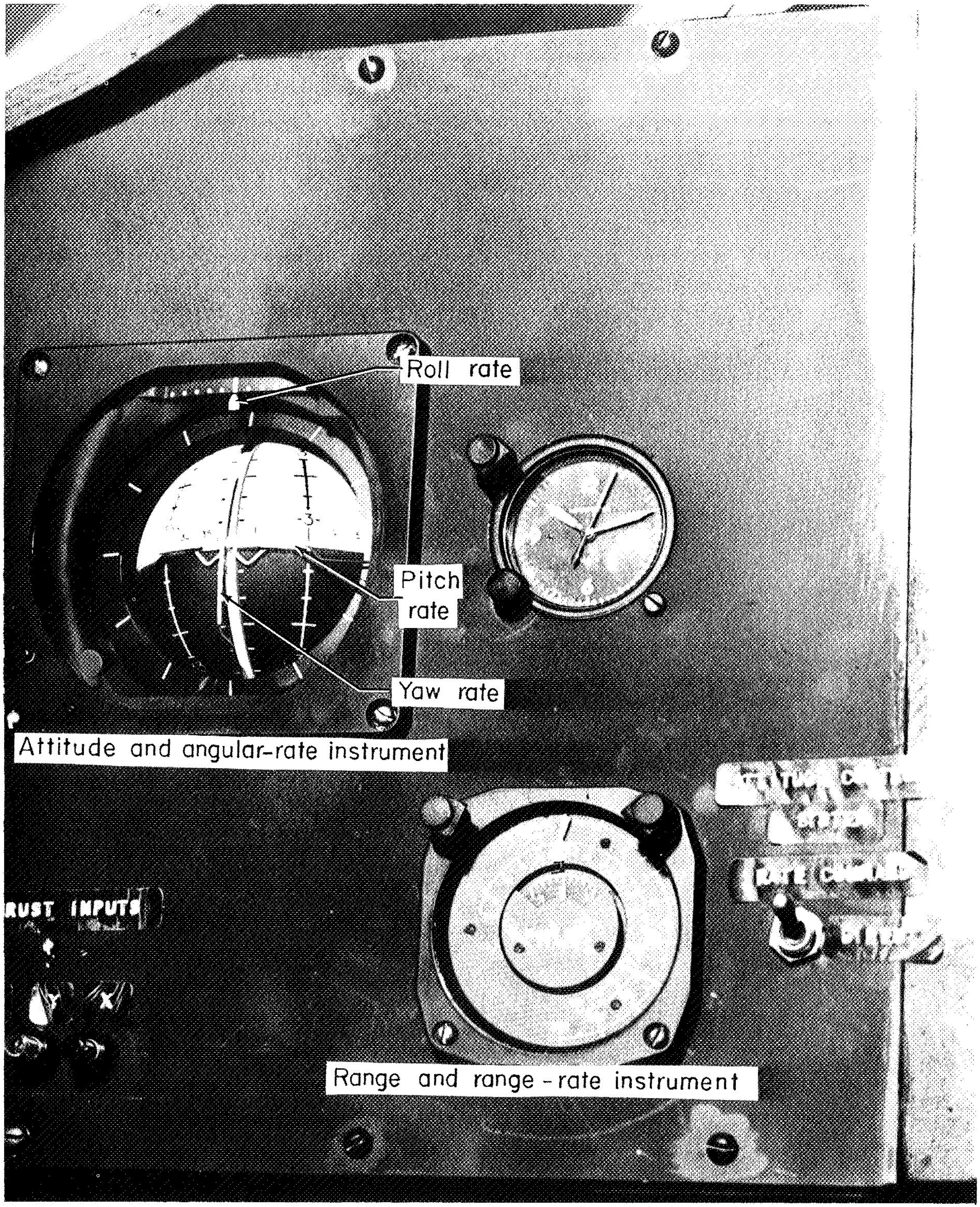
Figure 4.- Photographs of projected target image for fully illuminated condition showing target markings employed in simulation. Camera was located at approximate eye position of pilot. (Note: Vertical and horizontal bars mounted at rear of target are visual aids and were not present for data flights presented herein.)



L-63-7349

(a) Internal view of Gemini mock-up showing prototype hand controllers, angular-rate and attitude instrument, and range and range-rate instrument used in simulation.

Figure 5.- Instruments and hand controllers used in simulation.



(b) Closeup of instrument panel. L-63-7349.1

Figure 5.- Concluded.

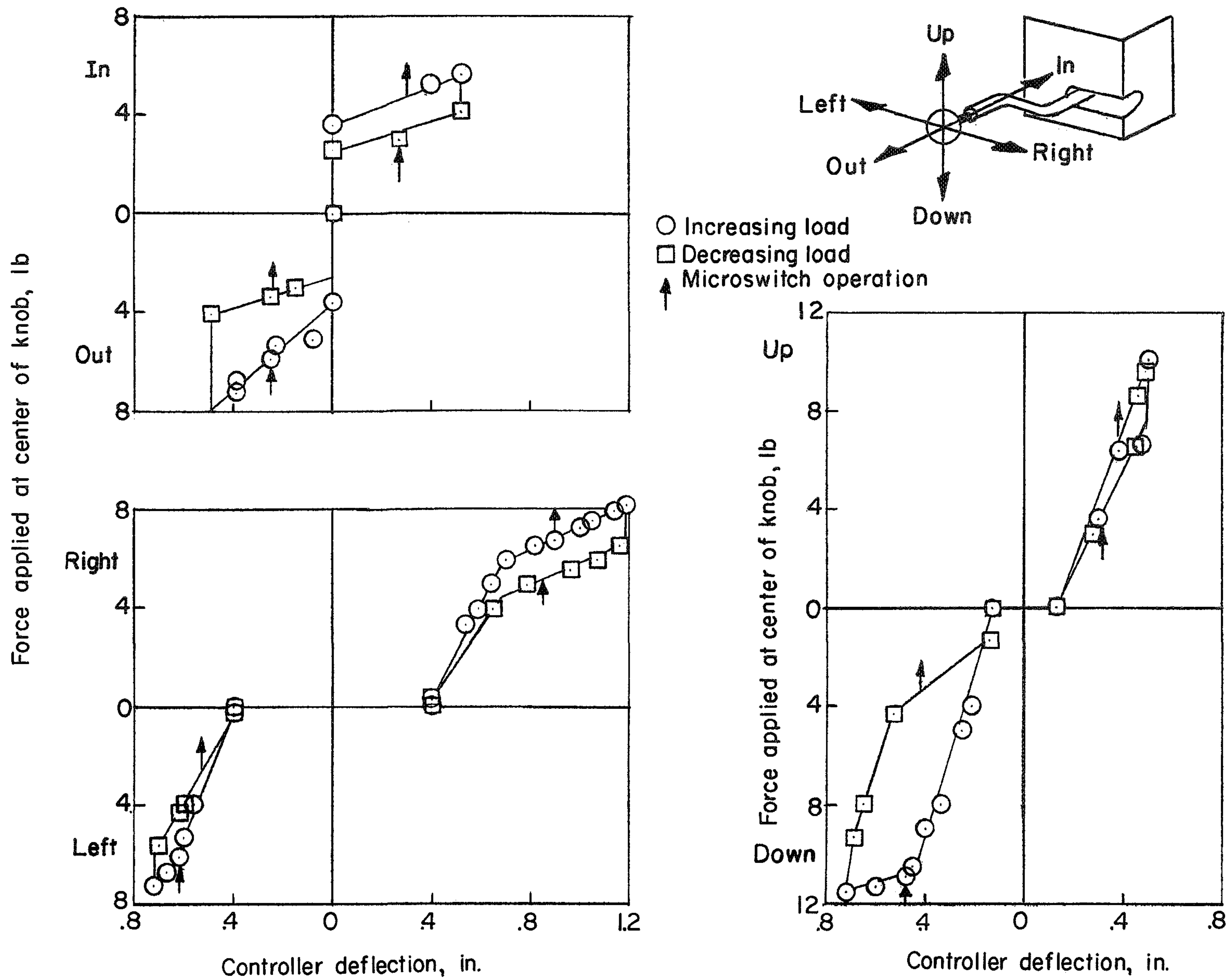


Figure 6.- Characteristics of translation controller.

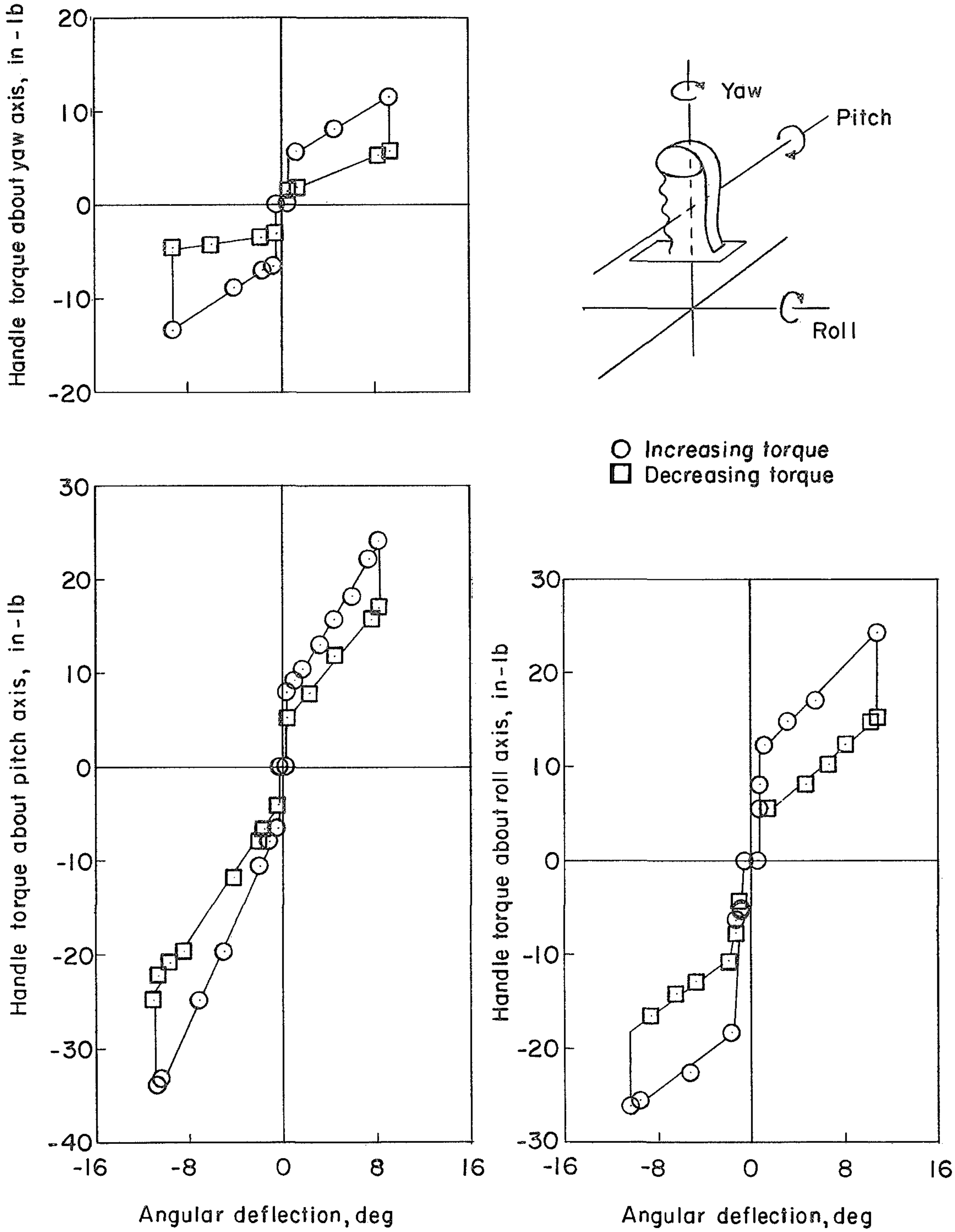
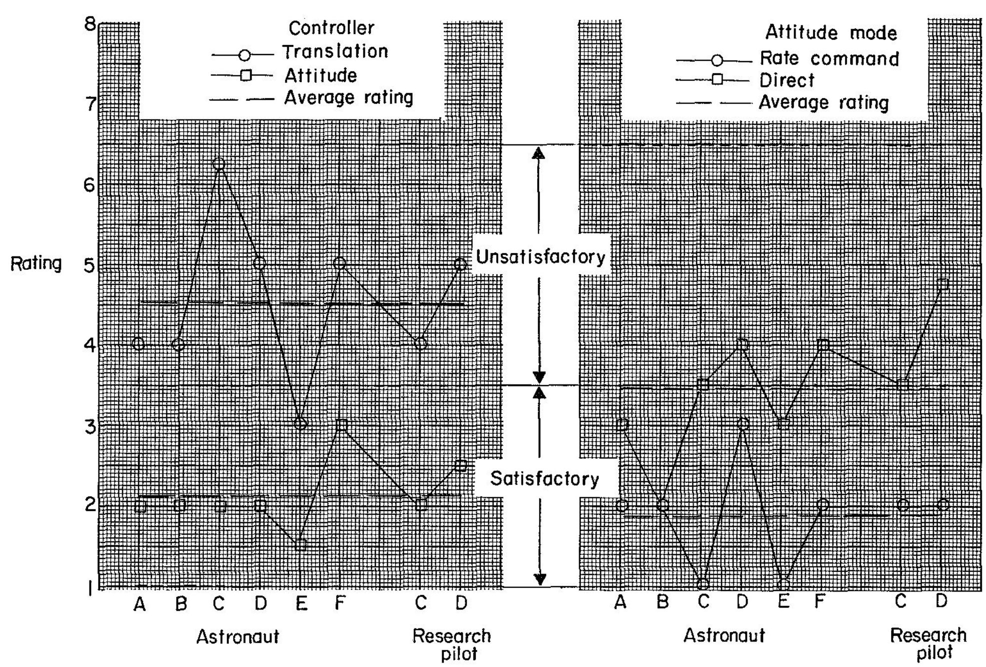


Figure 7.- Characteristics of attitude controller. (Arrows indicate positive directions of handle torques and deflections.)

Adjective rating	Numerical rating	Description
Satisfactory	1 2 3	Excellent, includes optimum Good, pleasant to fly Satisfactory, but with some mildly unpleasant characteristics
Unsatisfactory	4 5 6	Acceptable, but with unpleasant characteristics Unacceptable for normal operation Acceptable for emergency only
Unacceptable	7 8 9	Unacceptable even for emergency Unacceptable - dangerous Unacceptable - uncontrollable
Catastrophic	10	Motions possibly violent enough to prevent pilot escape

(a) Pilot-opinion rating schedule.



(b) Hand-controller ratings. (c) Attitude-mode ratings.

Figure 8.- Pilot ratings for hand controllers and attitude modes.

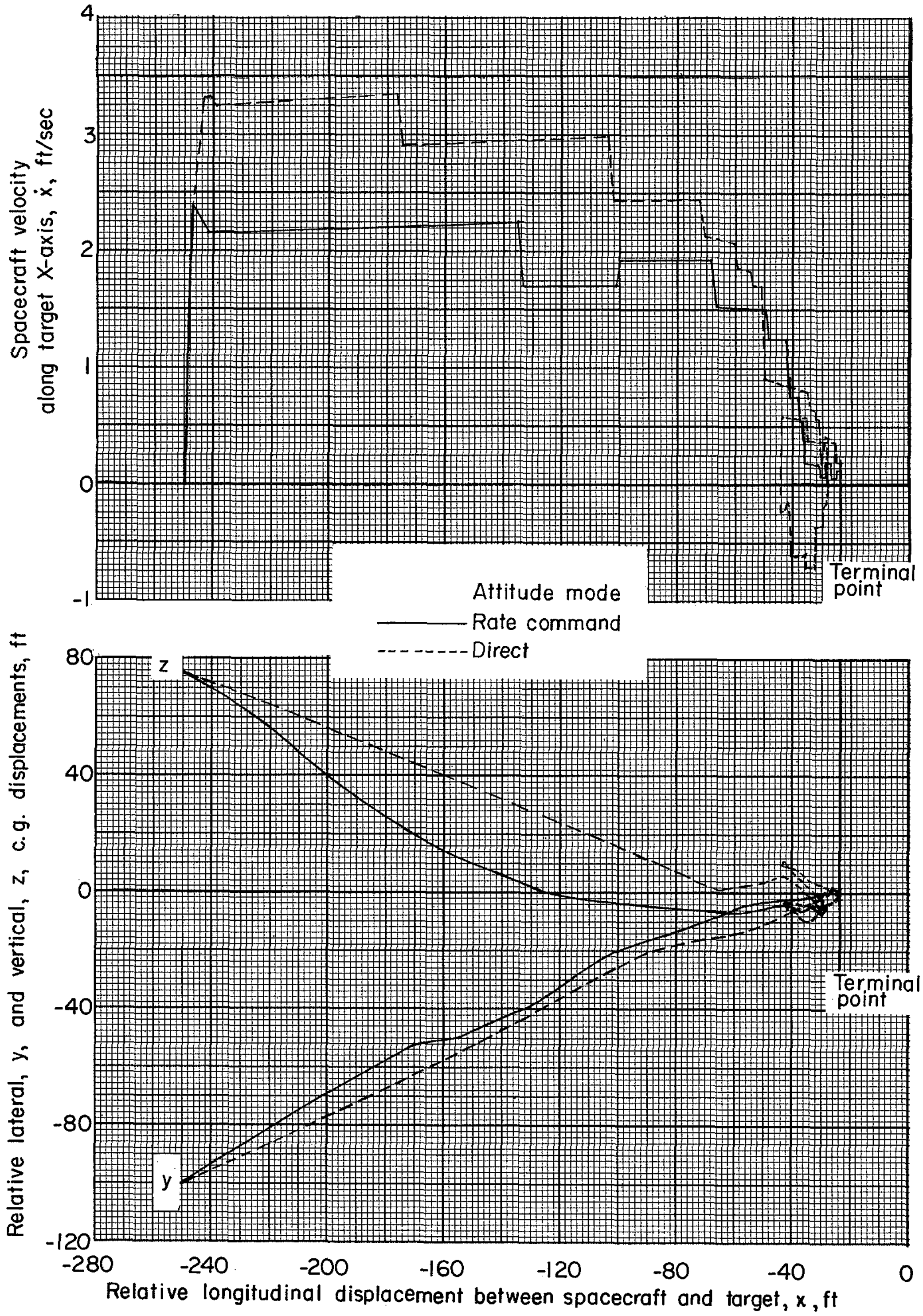
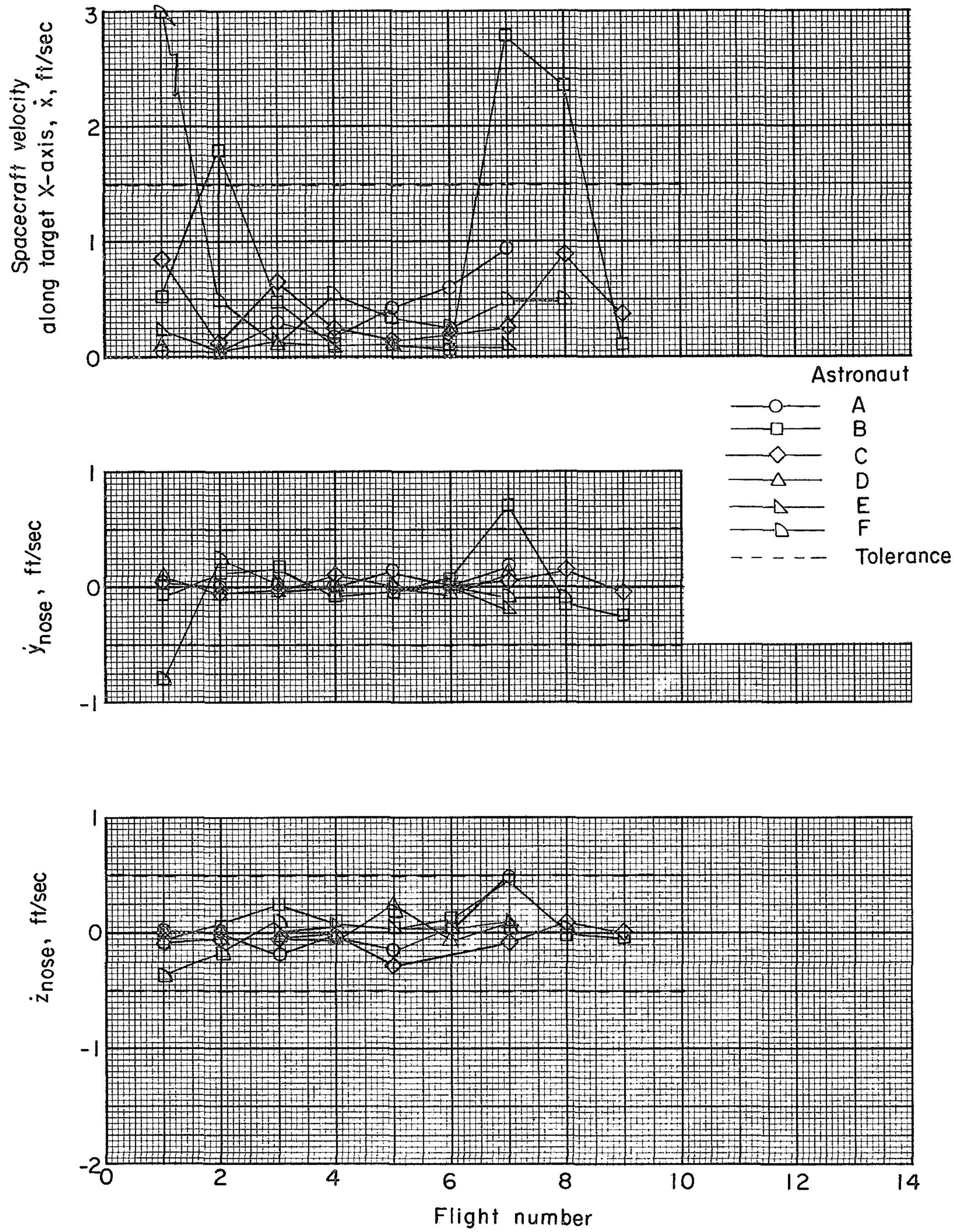
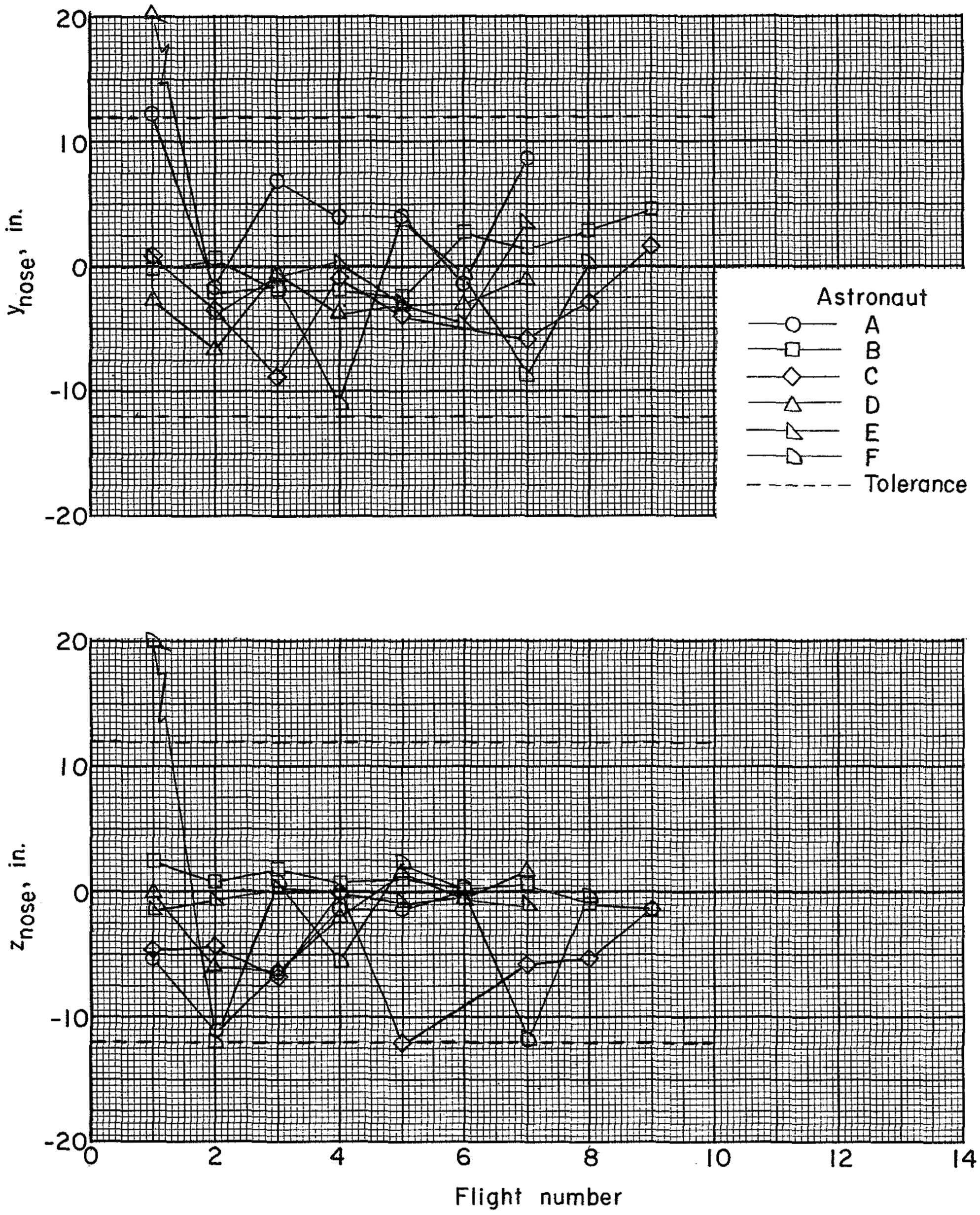


Figure 9.- Representative trajectories for astronaut E. Initial relative velocities are zero; $\psi_o = \theta_o = \phi_o = 15^\circ$.



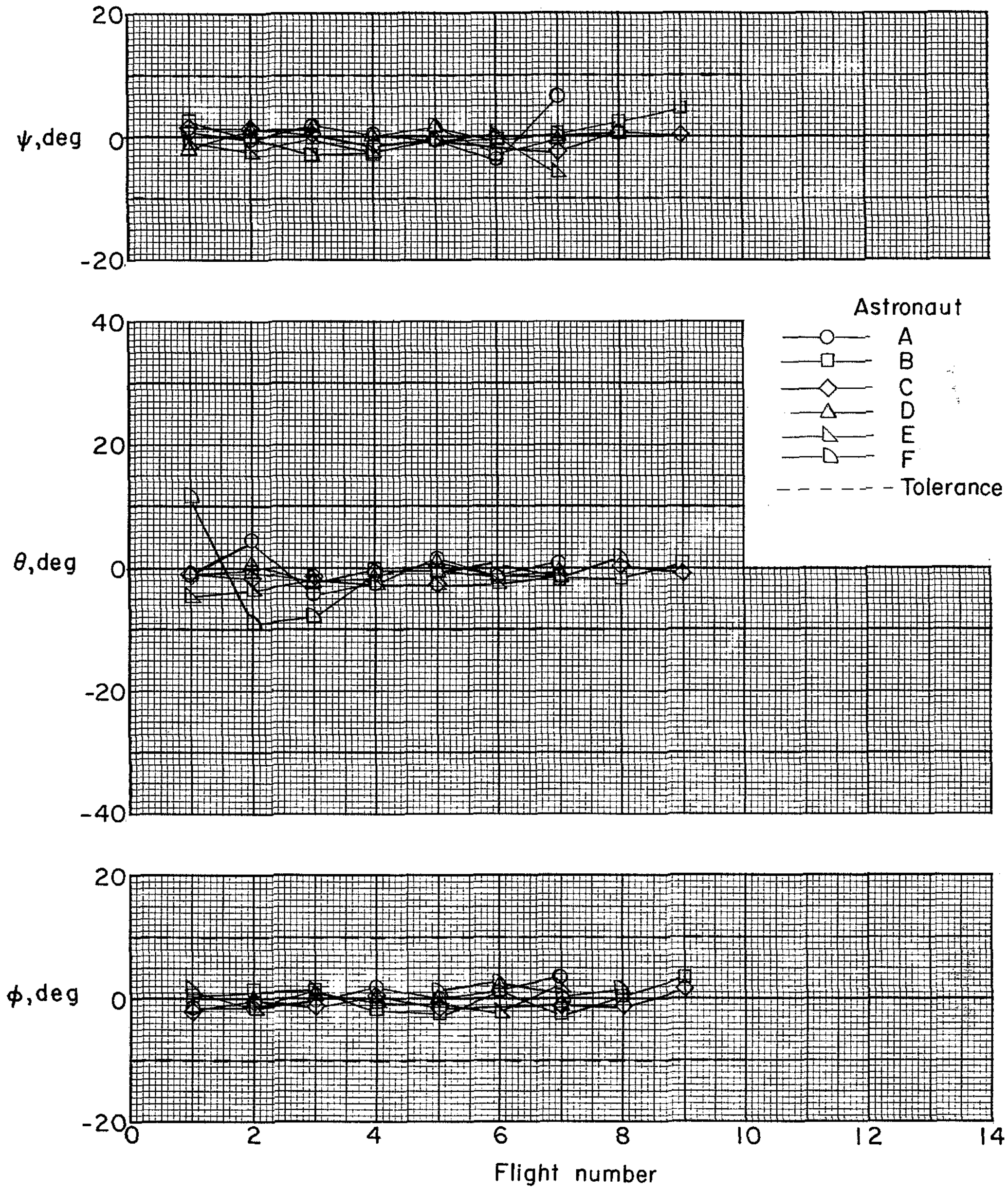
(a) $\dot{x}$, $\dot{y}$, and $\dot{z}$ at contact. (Flagged symbol indicates off-scale value.)

Figure 10.- Docking results of astronauts using rate-command attitude mode with deadband of 0.2 degree per second in each axis on Gemini instruments and hand controllers; fully lighted target.



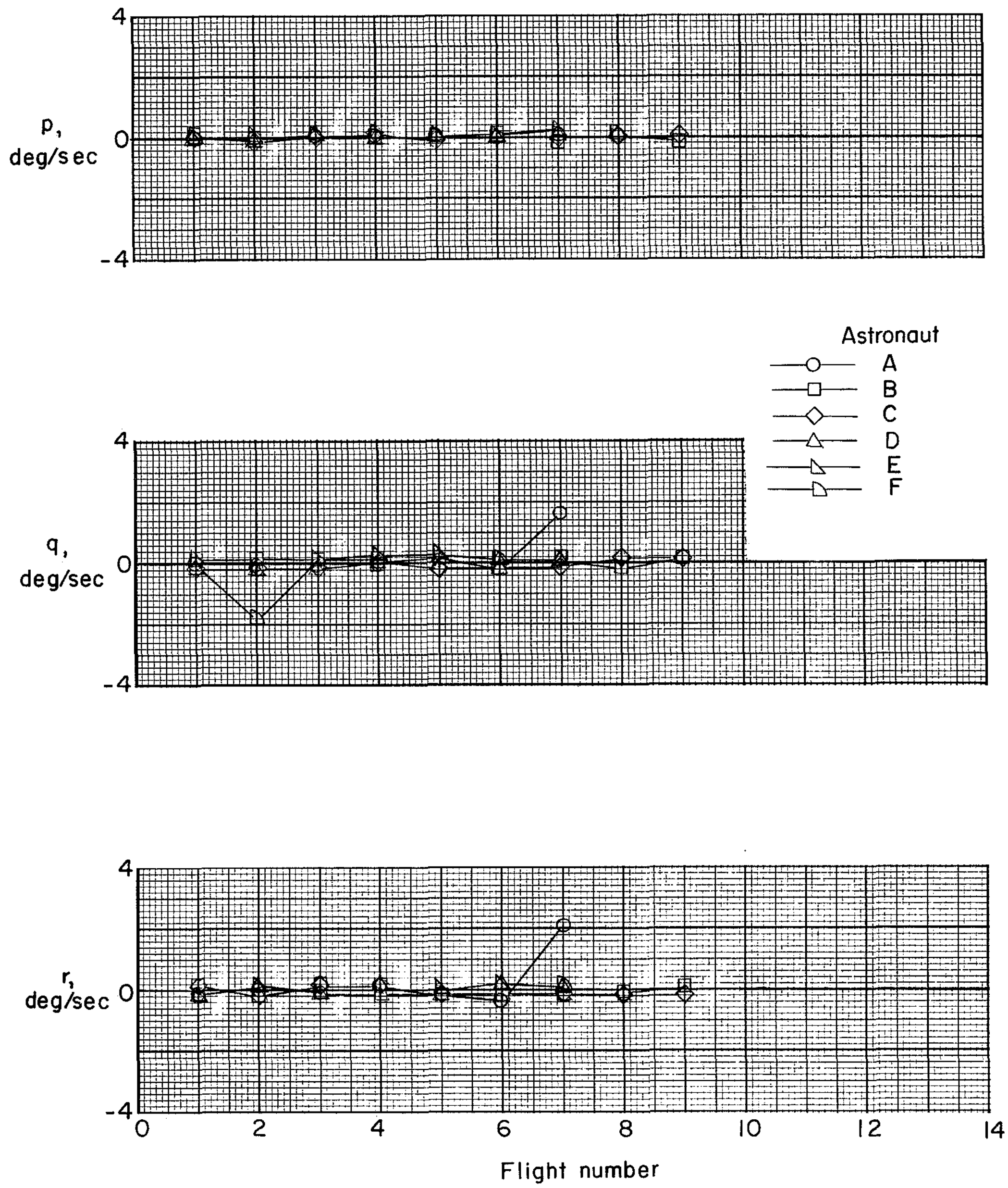
(b) Relative nose displacements at contact. (Flagged symbols indicate off-scale values.)

Figure 10.- Continued.



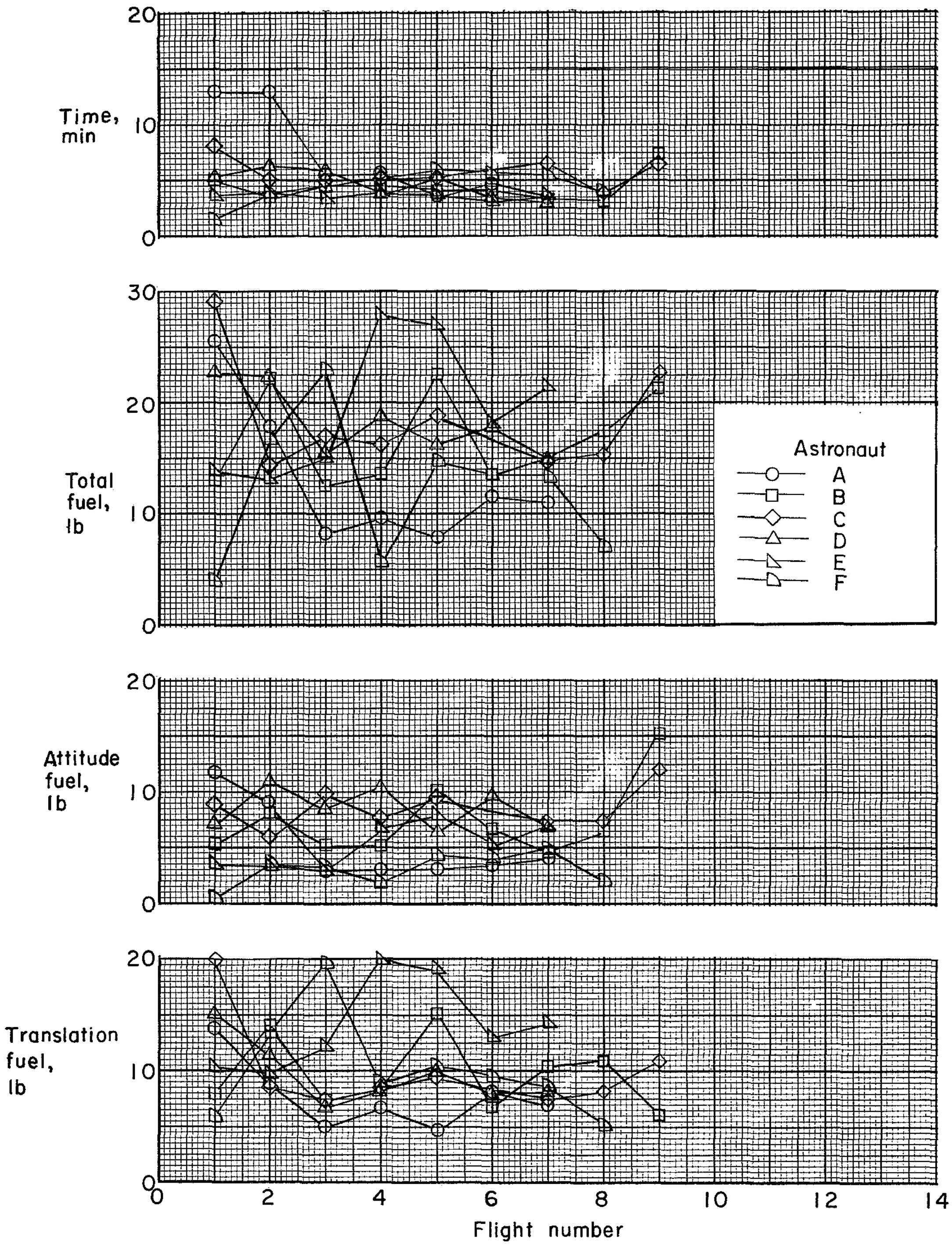
(c) Relative attitudes at contact.

Figure 10.- Continued.



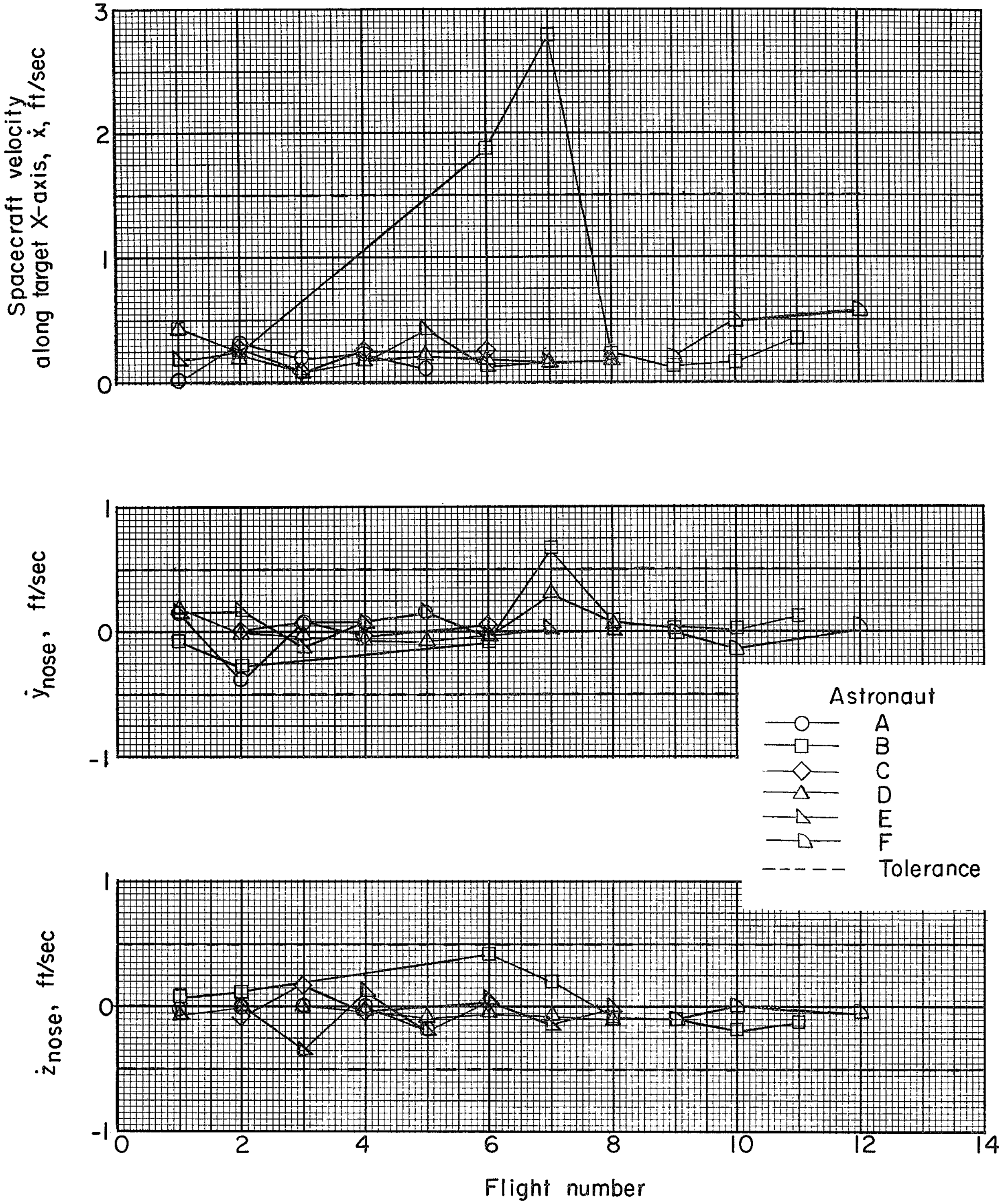
(d) Relative angular rates at contact.

Figure 10.- Continued.



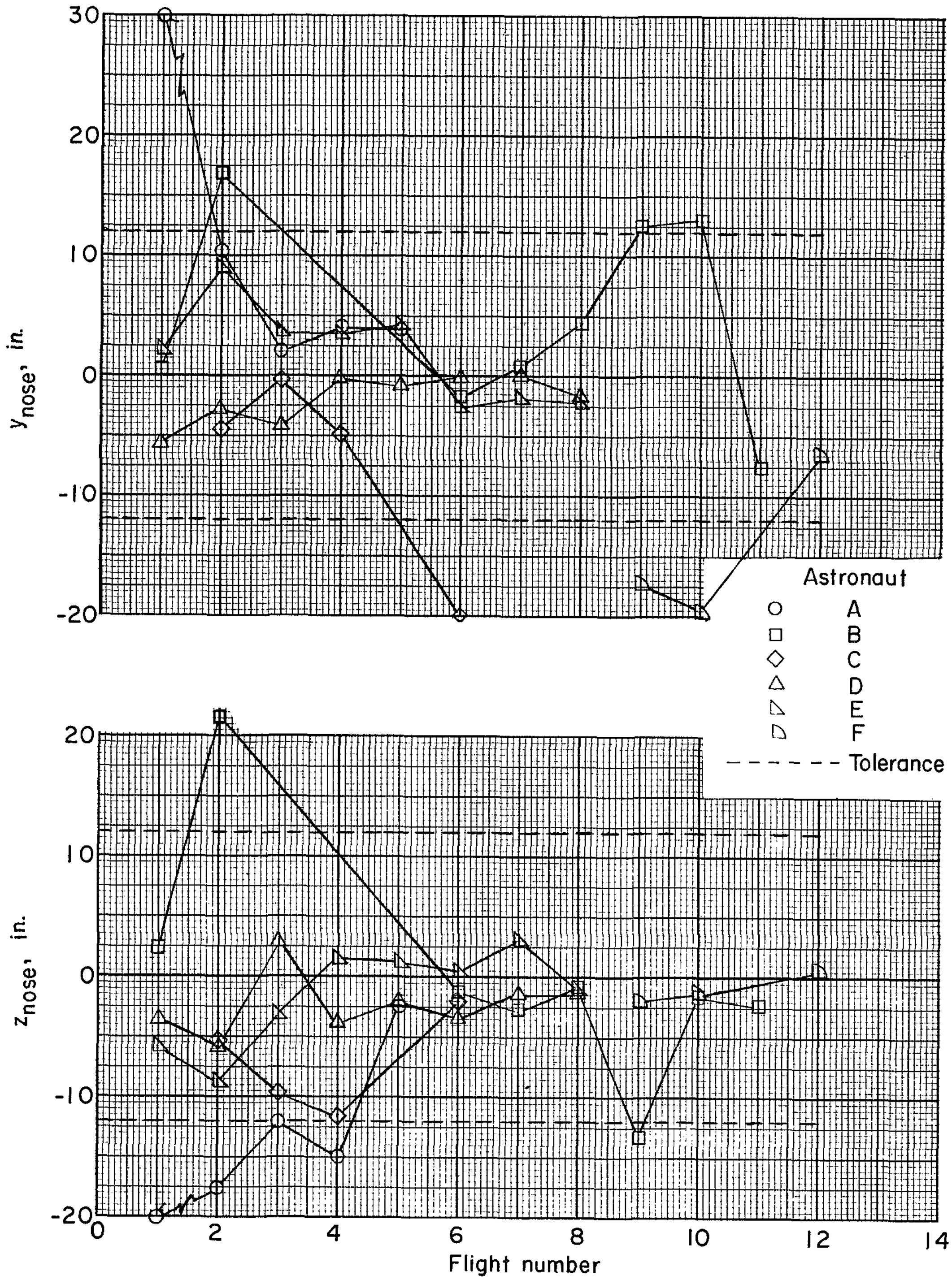
(e) Time required to complete docking flights and fuel used during flights.

Figure 10.- Concluded.



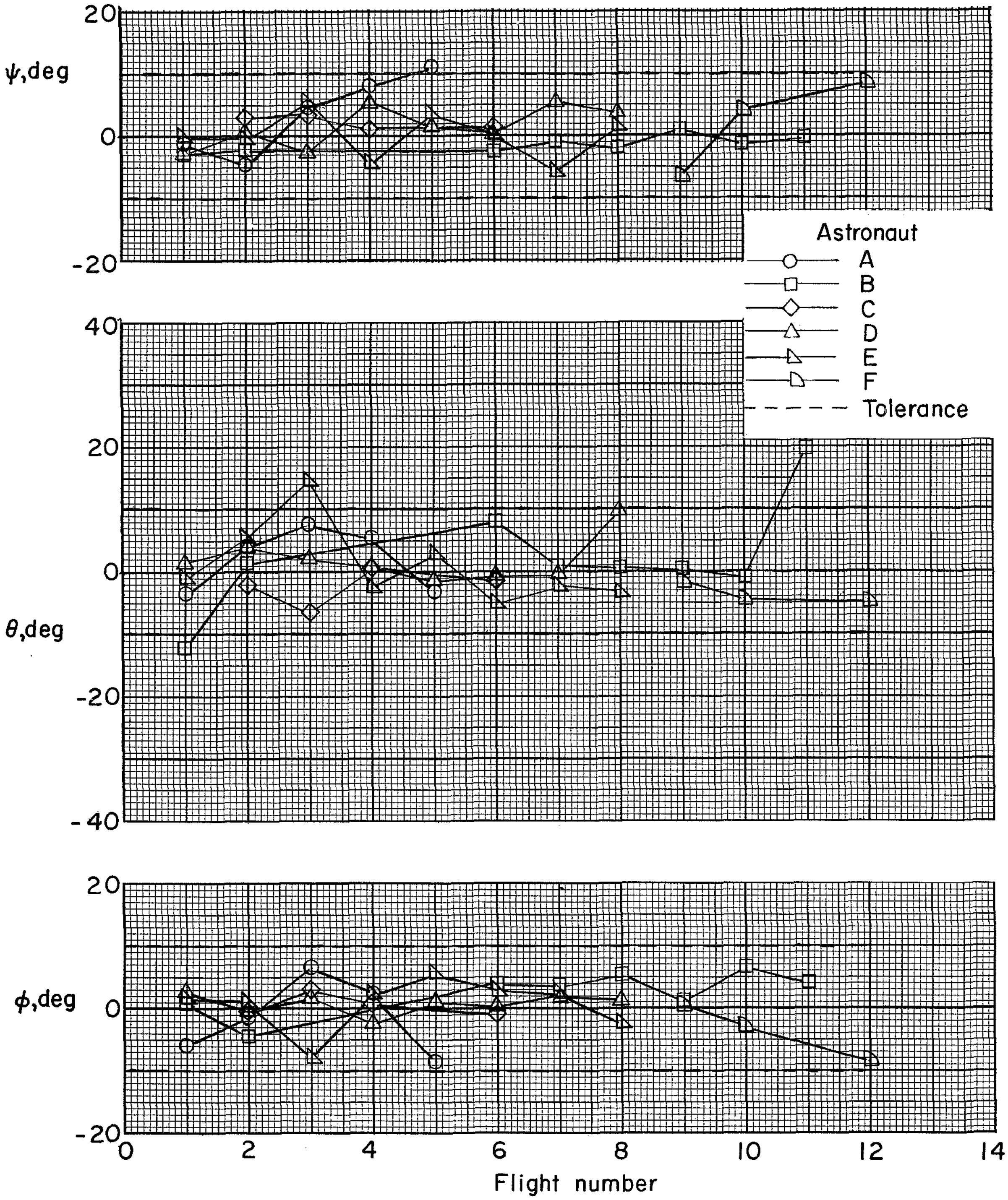
(a) $\dot{x}$, $\dot{y}$, and $\dot{z}$ at contact.

Figure 11.- Docking results of astronauts using direct attitude mode on Gemini instruments and hand controllers; fully lighted target.



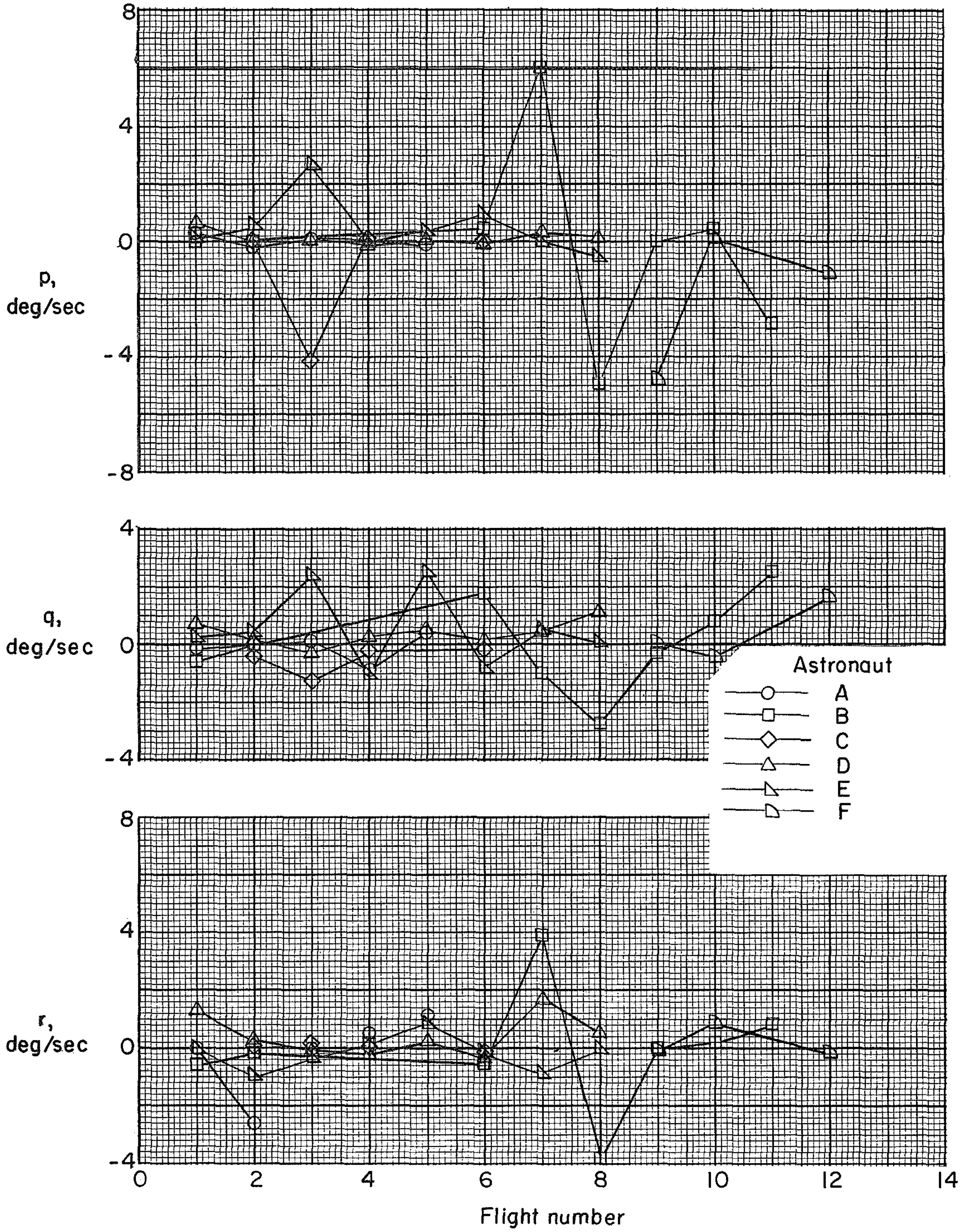
(b) Relative nose displacements at contact. (Flagged symbols indicate off-scale values.)

Figure 11.- Continued.



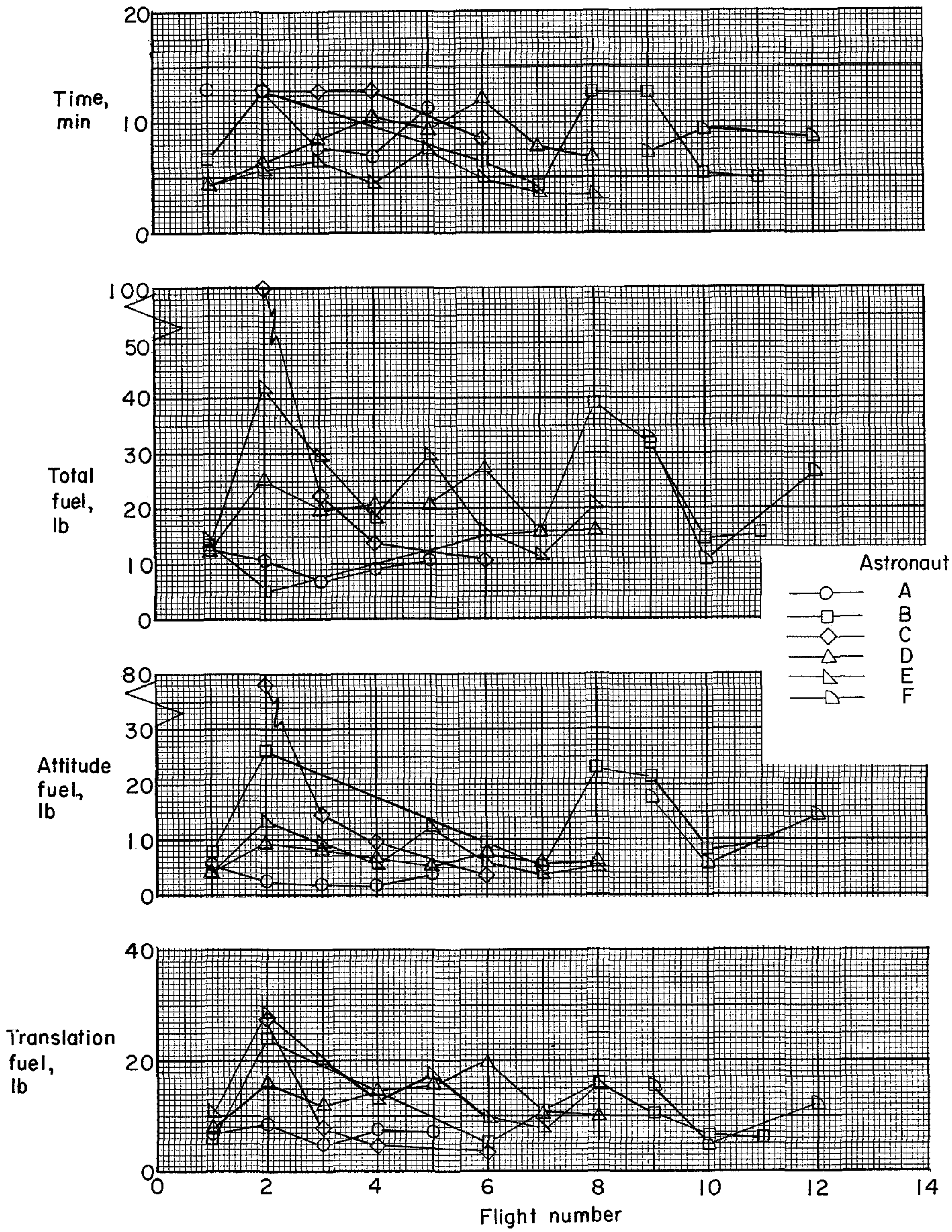
(c) Relative attitudes at contact.

Figure 11.- Continued.



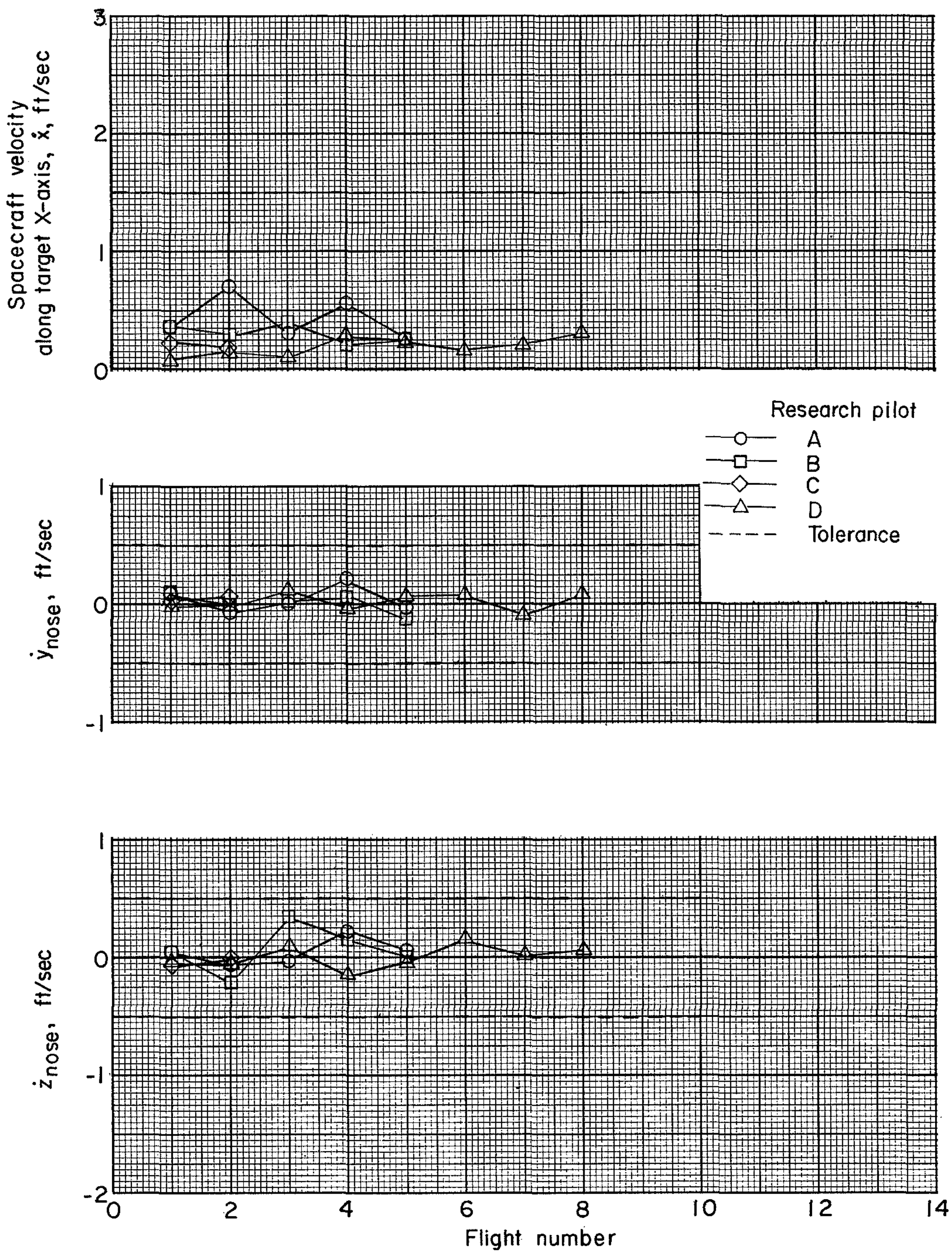
(d) Relative angular rates at contact.

Figure 11.- Continued.



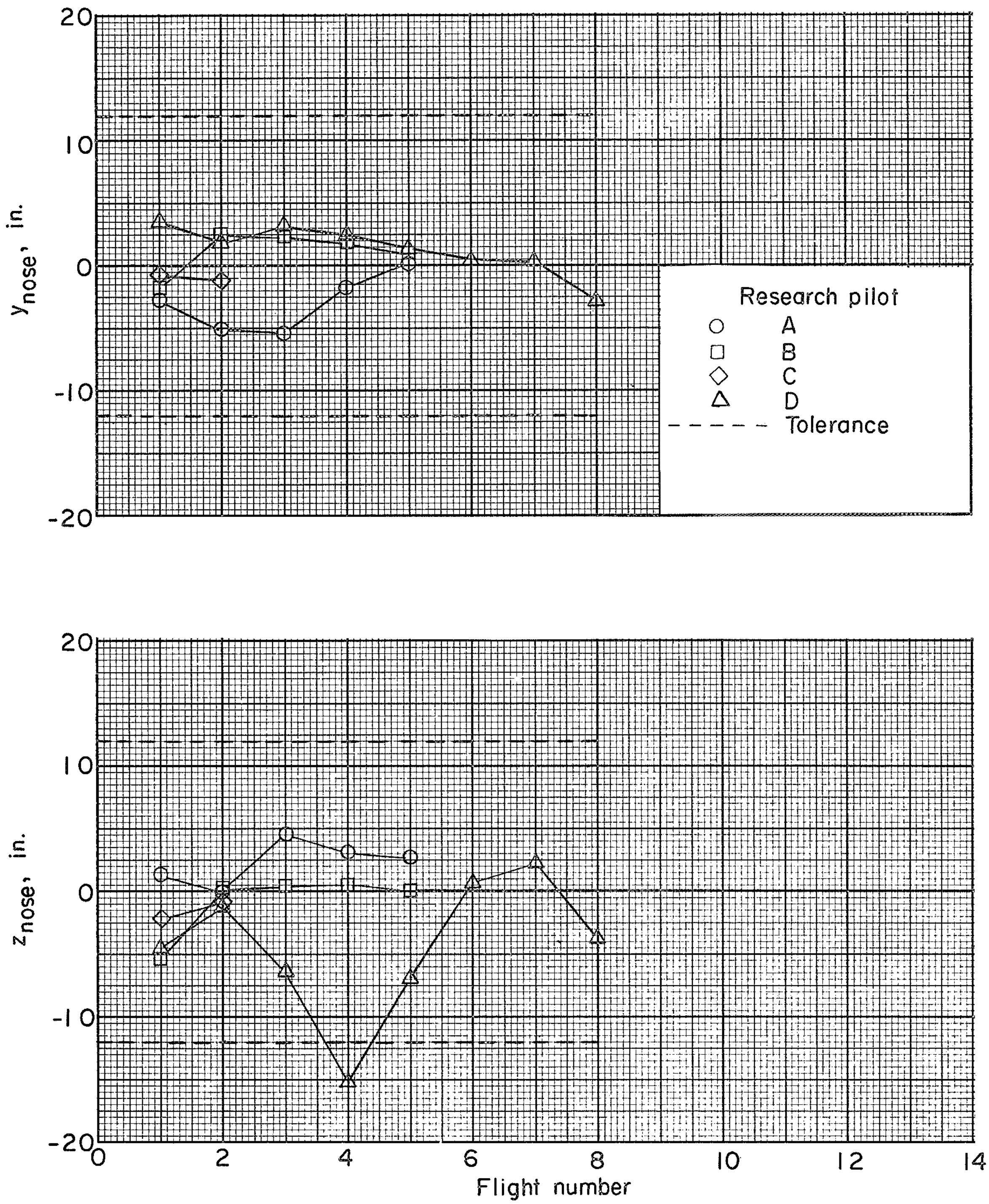
(e) Time required to complete docking flights and fuel used during flights.

Figure 11.- Concluded.



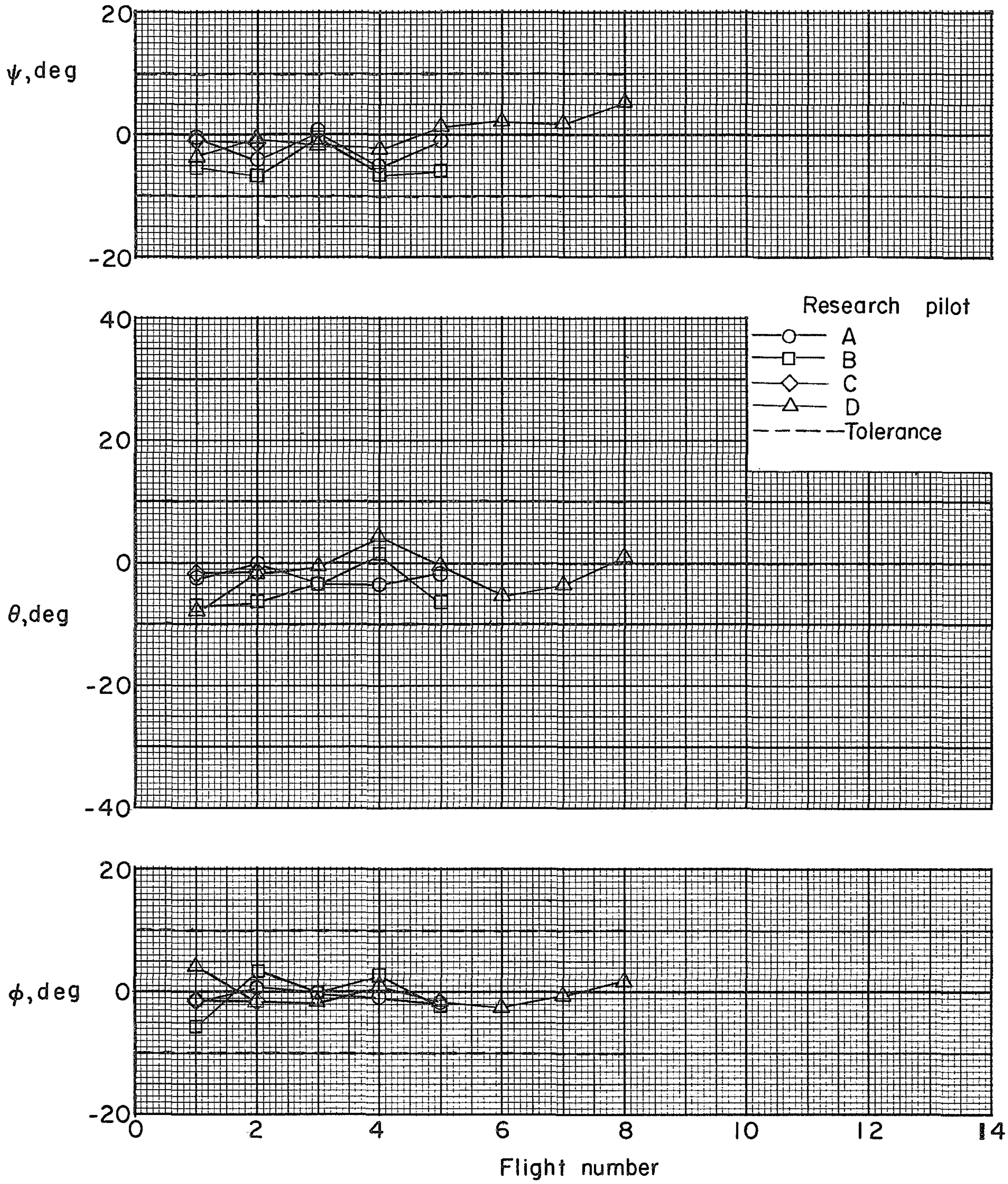
(a) $\dot{x}$, $\dot{y}$, and $\dot{z}$ at contact.

Figure 12.- Docking results of research pilots using rate-command attitude system with deadband of 0.2 degree per second in each axis on Gemini instruments and hand controllers; fully lighted target.



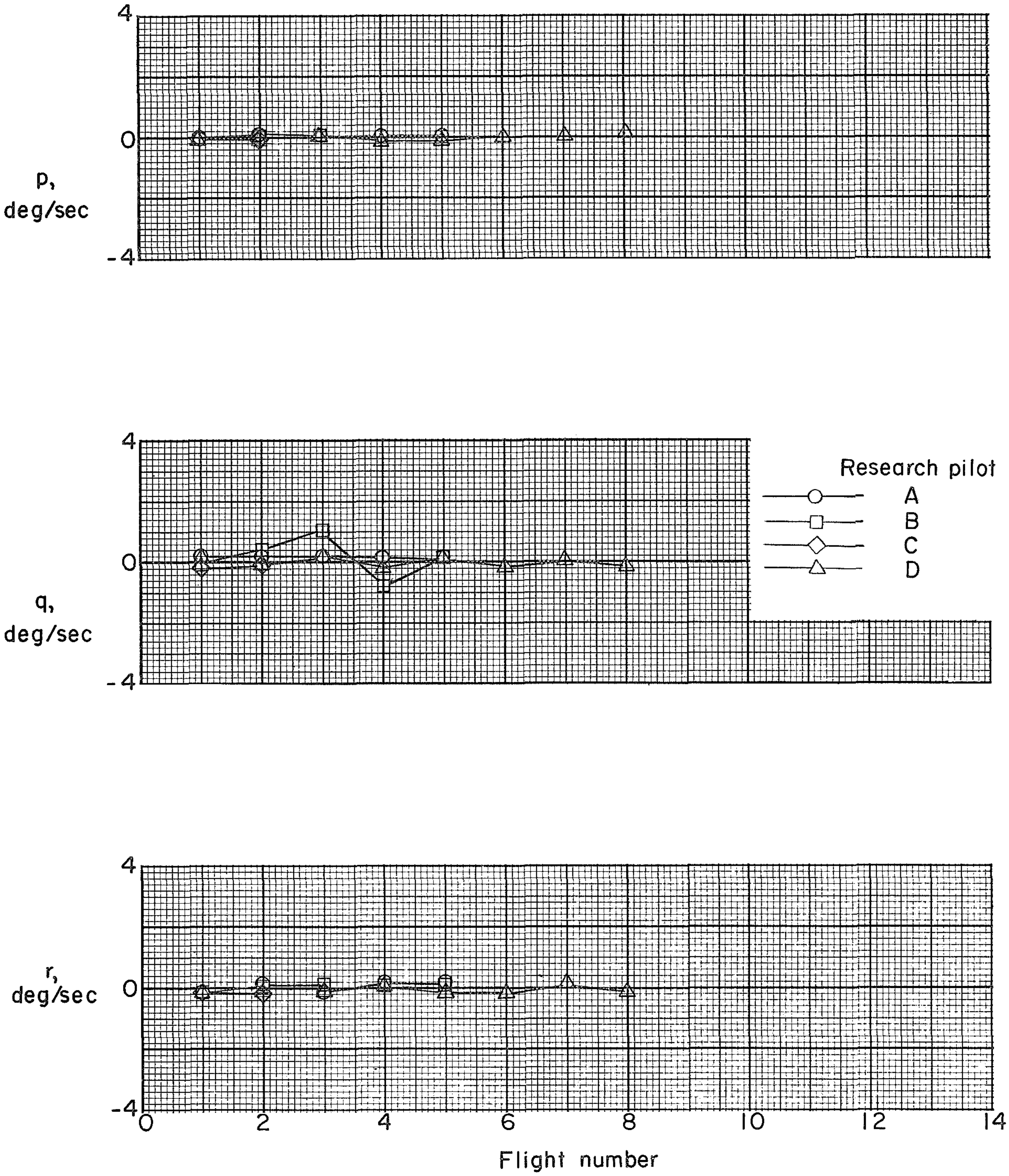
(b) Relative nose displacements at contact.

Figure 12.- Continued.



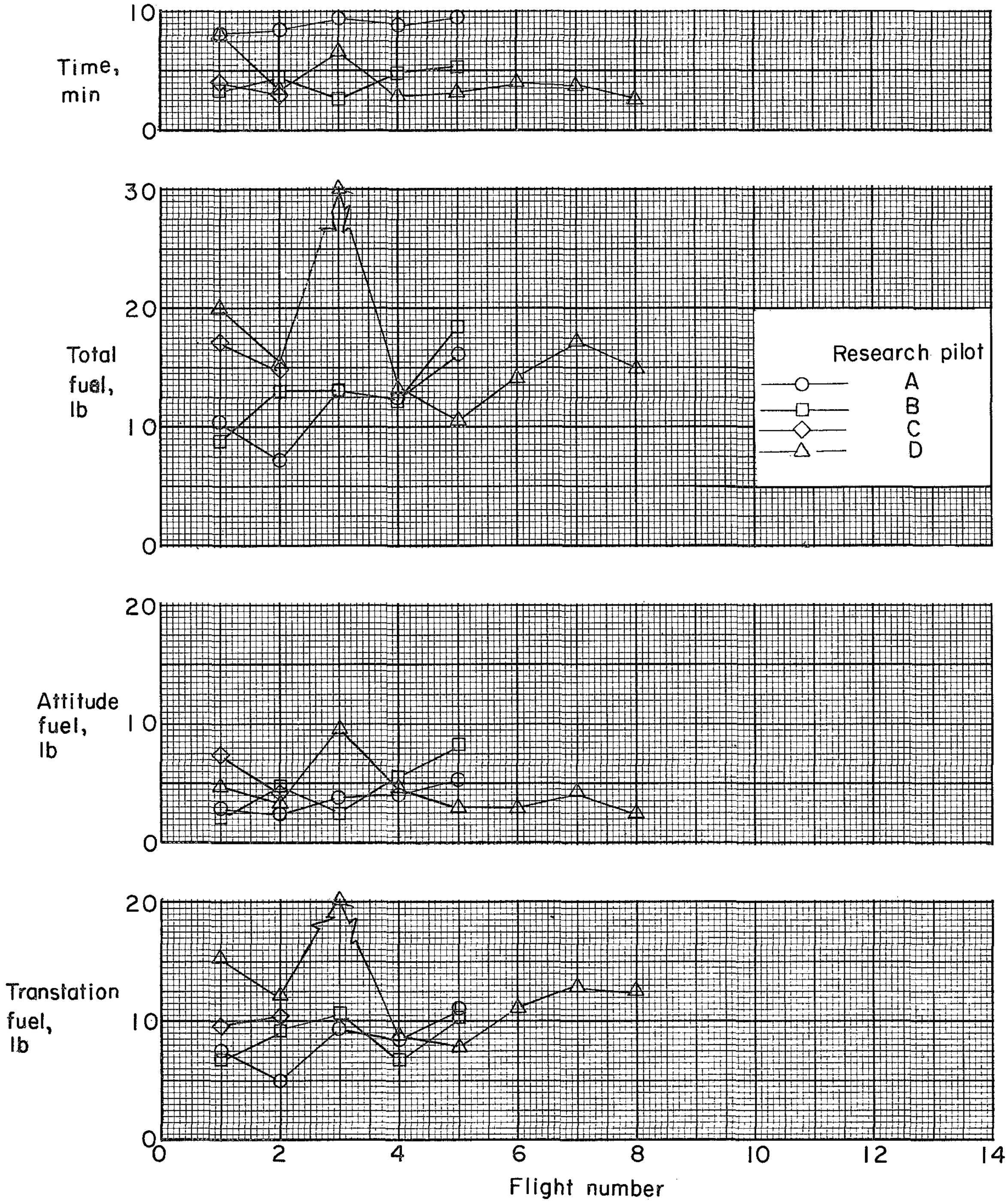
(c) Relative attitudes at contact.

Figure 12.- Continued.



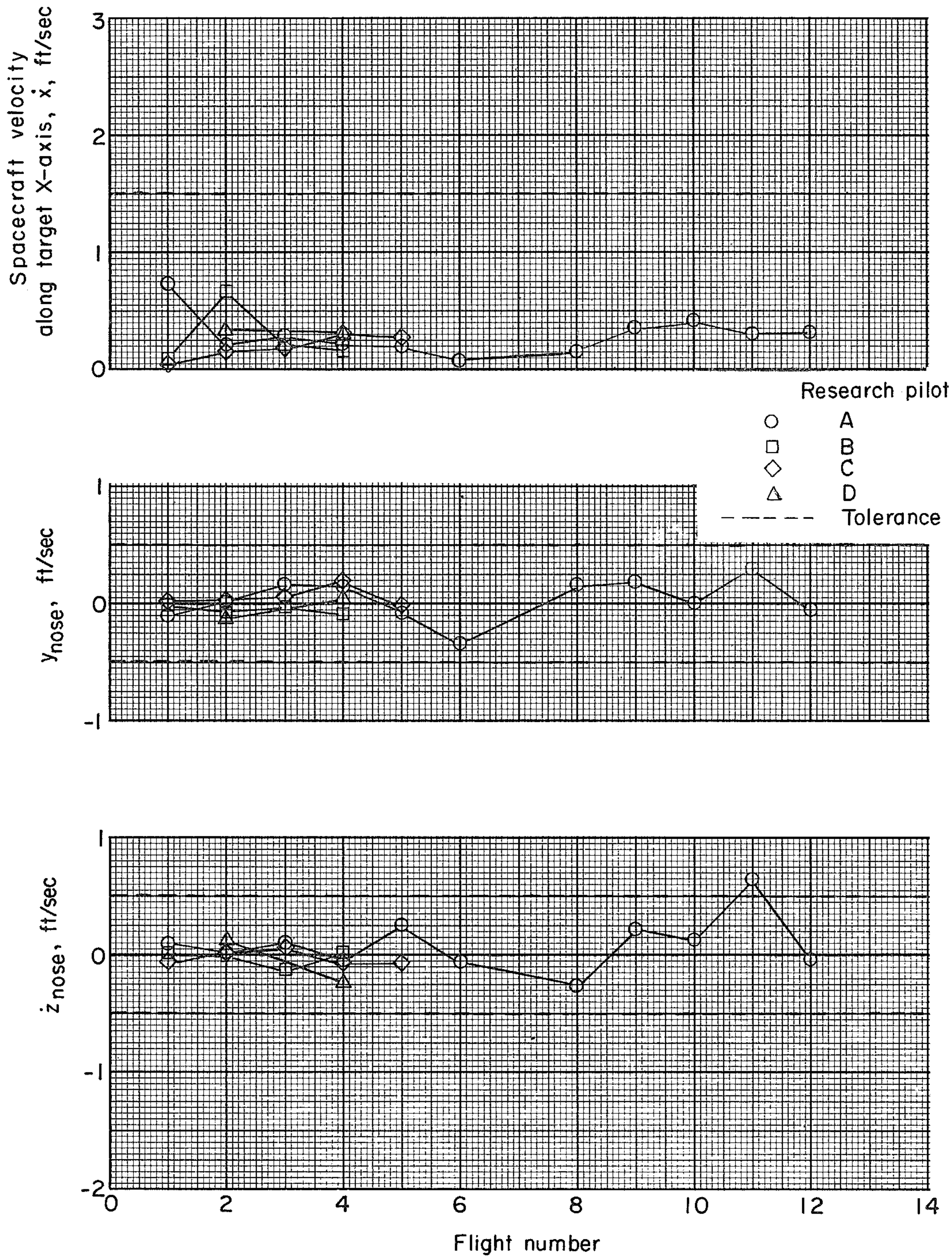
(d) Relative angular rates at contact.

Figure 12.- Continued.



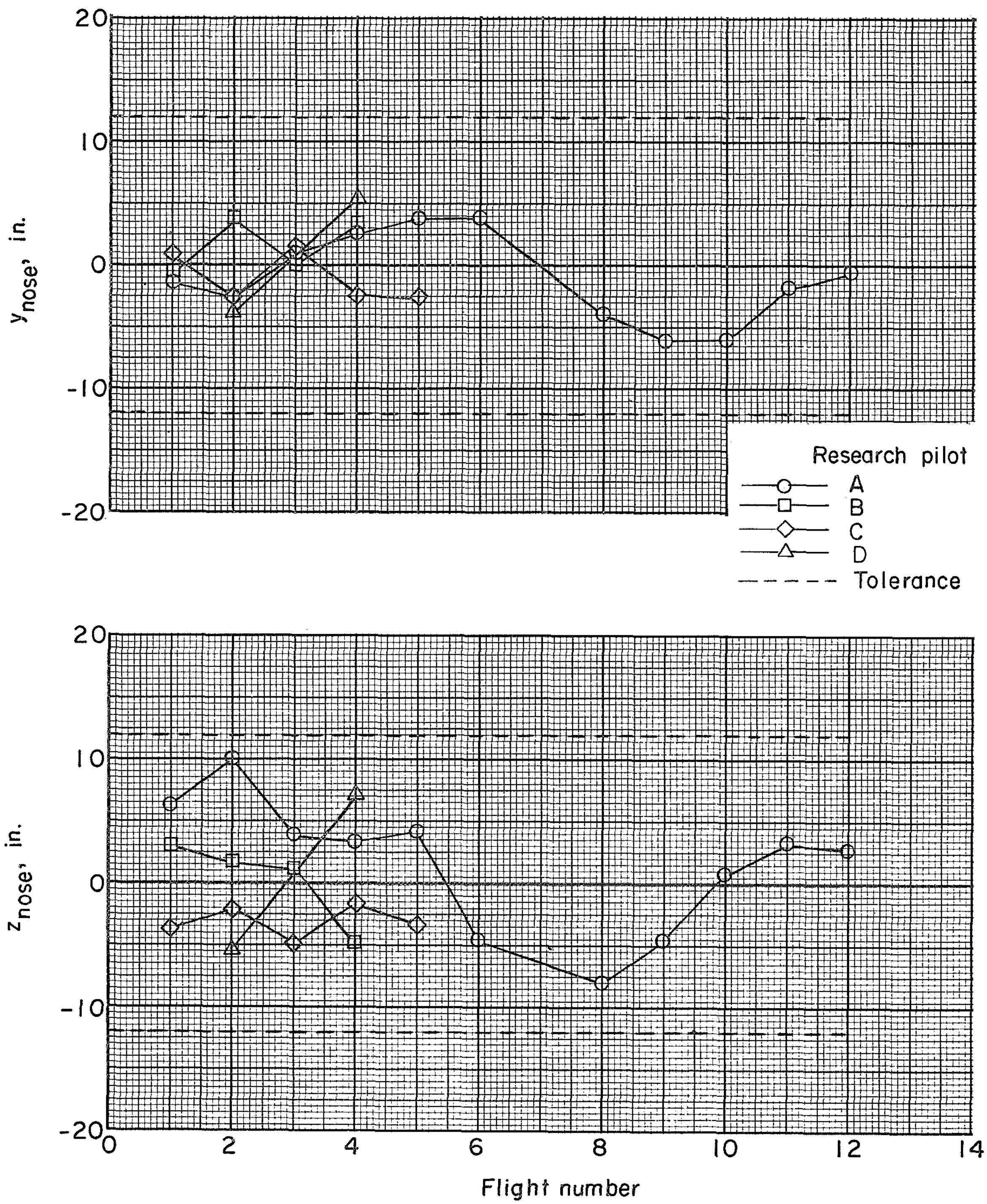
(e) Time required to complete docking flights and fuel used during flights. (Flagged symbols indicate off-scale values.)

Figure 12.- Concluded.



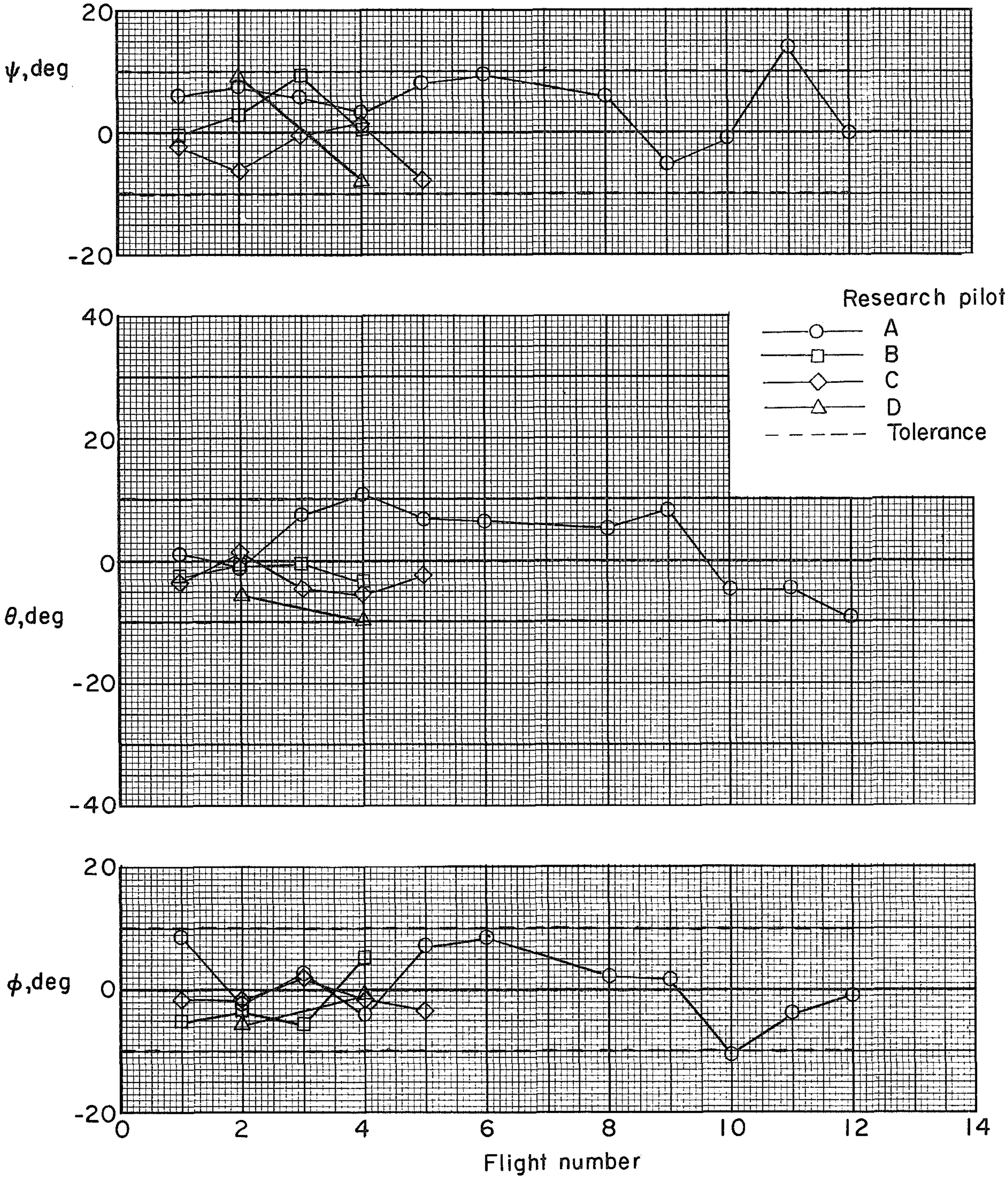
(a) $\dot{x}$, $\dot{y}$, and $\dot{z}$ at contact.

Figure 13.- Docking results of research pilots using direct attitude mode on Gemini instruments and hand controllers; fully lighted target.



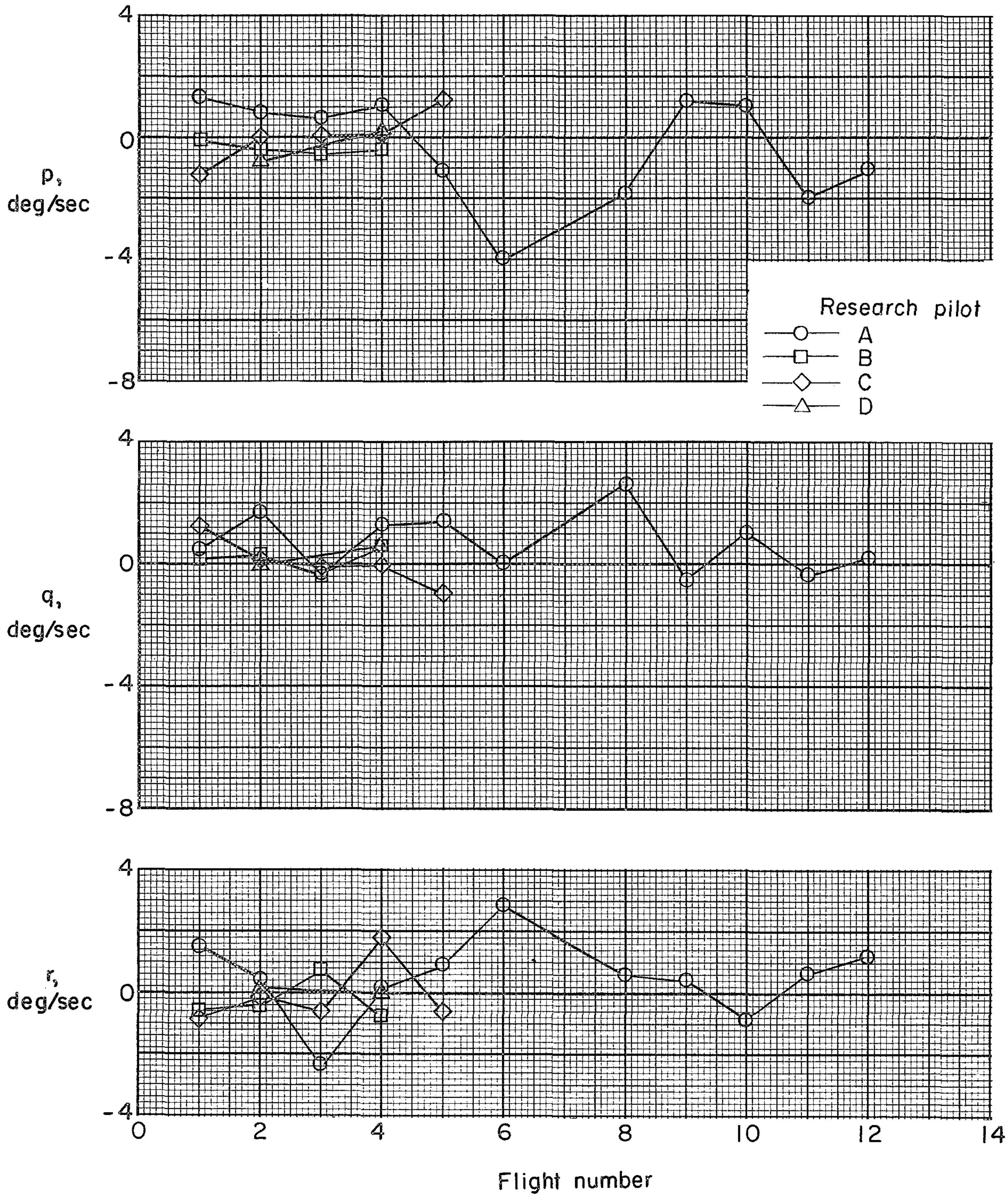
(b) Relative nose displacements at contact.

Figure 13.- Continued.



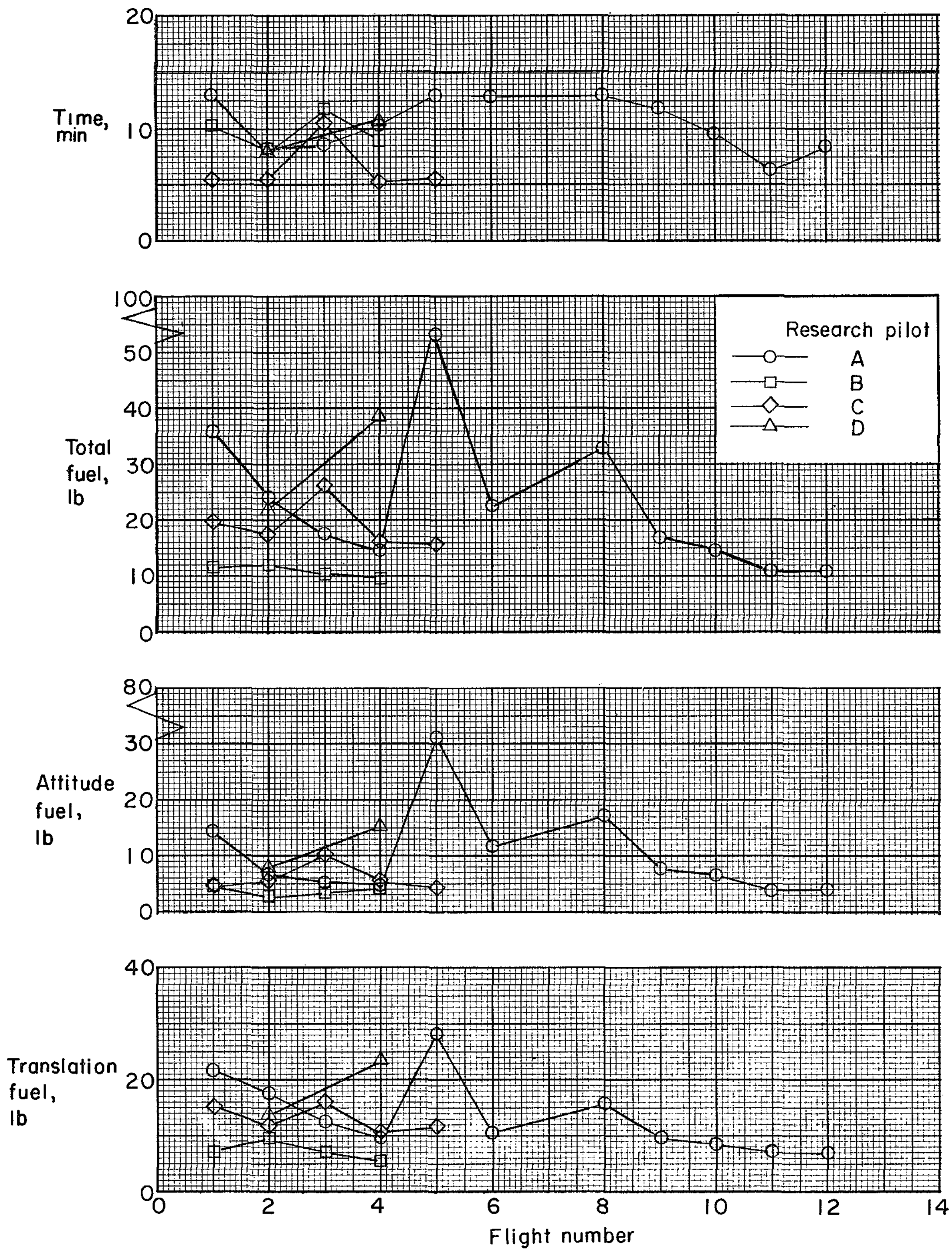
(c) Relative attitudes at contact.

Figure 13.- Continued.



(d) Relative angular rates at contact.

Figure 13.- Continued.



(e) Time required to complete docking flights and fuel used during docking flights.

Figure 13.- Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546